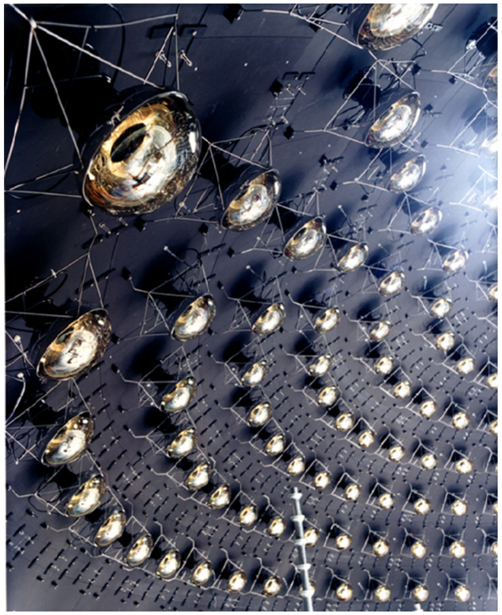
Expect the Unexpected: Neutrino Physics at MiniBooNE

Sam Zeller
Fermilab

Aditya Sambamurti Memorial Lecture

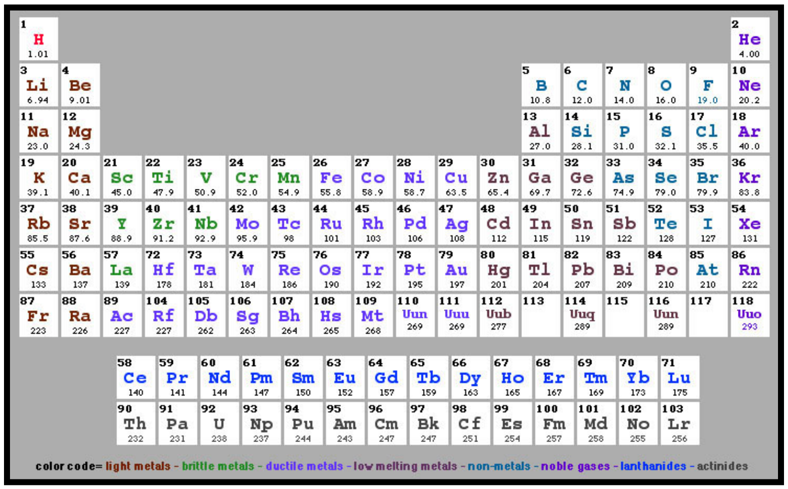
July 20, 2010

- what are neutrinos?
- neutrino history
  - full of surprises
  - neutrino oscillations
- MiniBooNE experiment
- recent developments

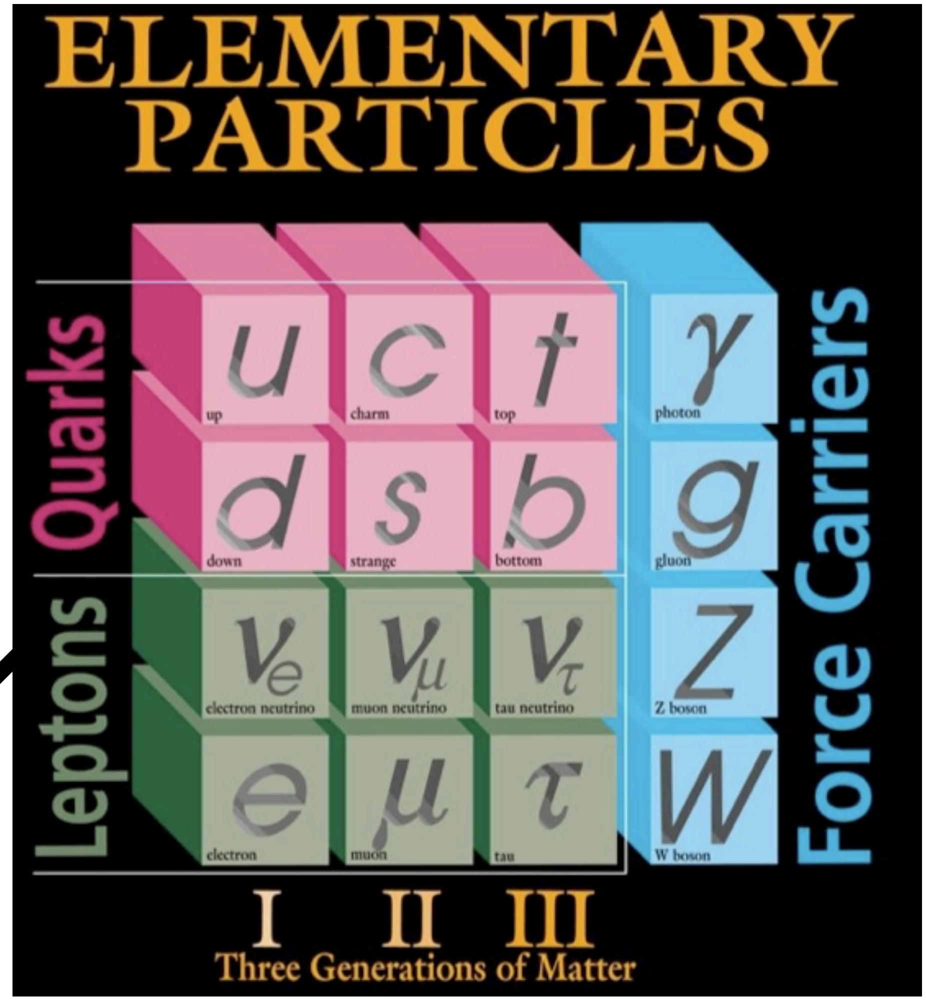


"Standard Model"

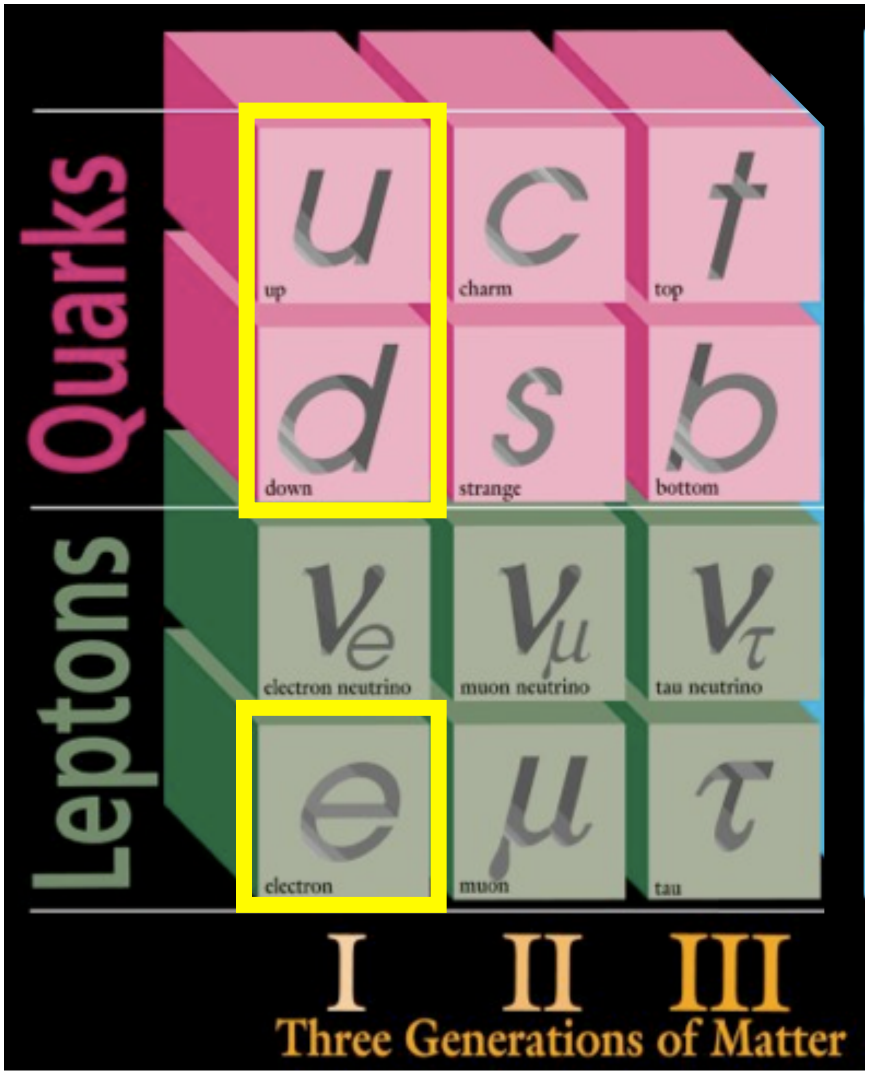
just like chemists have
the periodic table:



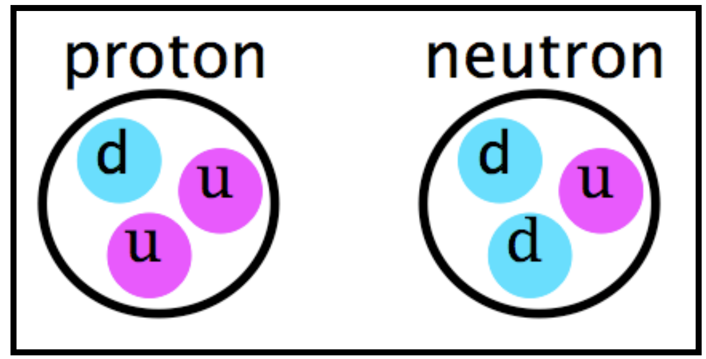
particle physicists
have **"standard model"**
of elementary particles



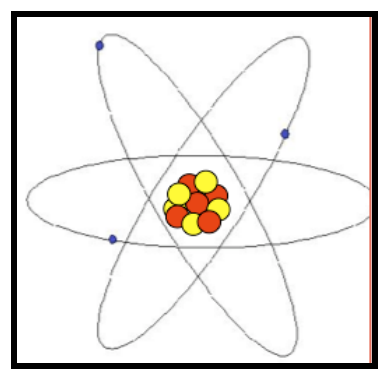
Standard Model



- many of these particles should be familiar to you



- e, p, and n bundled together to form atoms



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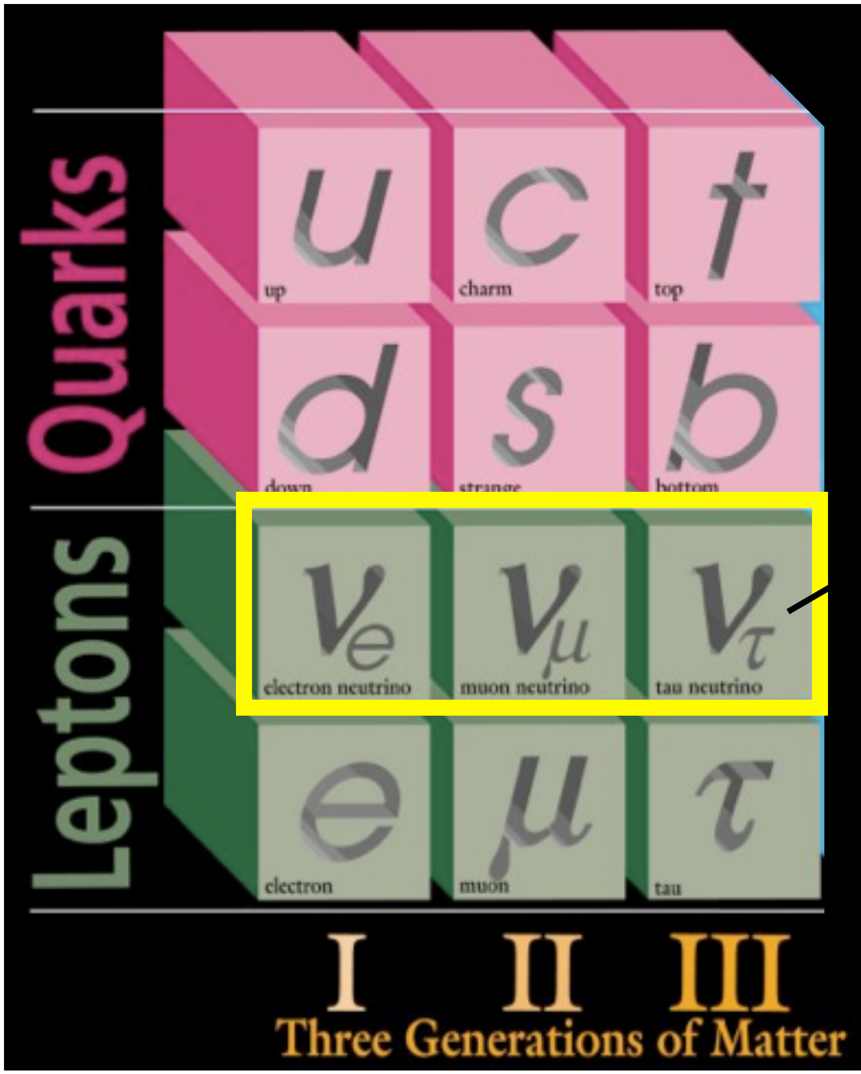


what we know about neutrinos:

- no electric charge
- no mass (according to SM)
- three types ("flavors")
- each paired with an electrically charged partner (e,μ,τ)

Neutrinos Are Everywhere

- together with photons, neutrinos are by far the most abundant particles in the universe …

ν's power the sun

ν's shower down on the earth

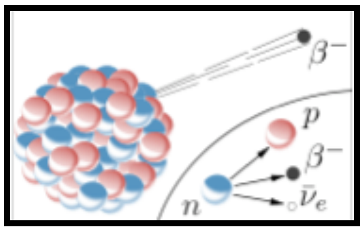
ν's drive supernovae explosions

even emitted by bananas!

- their history has been rich in surprises (and Nobel prizes) …

Surprise! Neutrinos Exist?!

1930: Wolfgang Pauli introduces a new, elusive subatomic particle which carries away missing energy in β decay



$n \rightarrow p\ e^{-}\ \overline{\nu}_e$

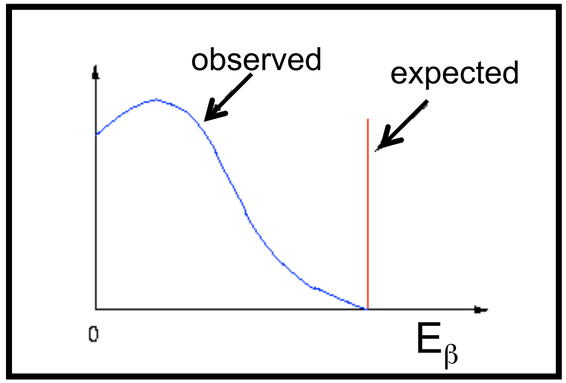


Photo: AIP, Emilio Segrè Visual Archives

- saves energy conservation
- introduces a brand new particle: neutrino!
  - no charge, no mass
  - only interact weakly
- worried that scientists may never detect

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Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Photo: AIP, Emilio Segrè Visual Archives

Dear **Radioactive** Ladies and Gentlemen,

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Photo: AIP, Emilio Segrè Visual Archives

I have hit upon a **drastic remedy** to save … the law of conservation of energy

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Photo: AIP, Emilio Segrè Visual Archives

But so far I do **not dare** publish anything about this idea …

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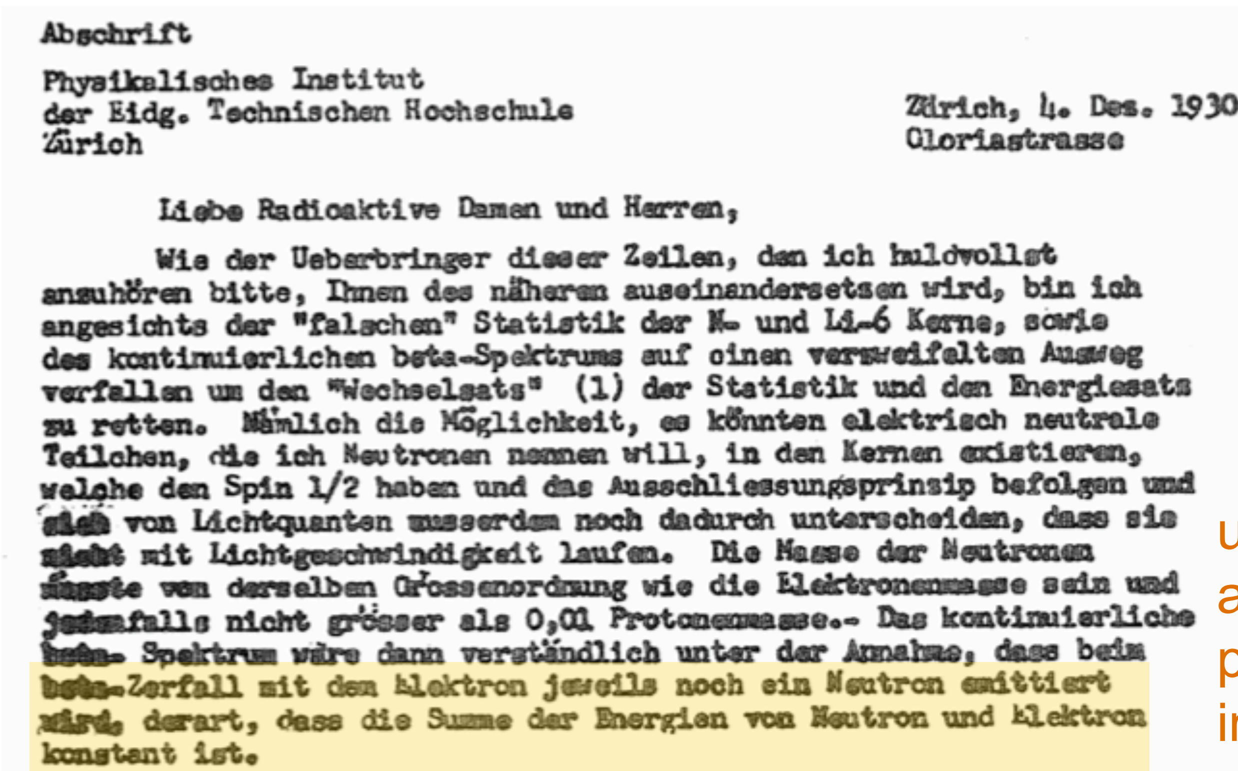

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Photo: AIP, Emilio Segrè Visual Archives

unfortunately, I will not be able to appear in Tübingen personally, because I am indispensable **due to a ball** which will take place in Zurich …

Your humble servant,
W. Pauli

ν's Do Not Interact Very Often

- neutrinos interact only **weakly**

"The chances of a ν actually hitting something as it travels … are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich"

- Douglas Adams
(author of The Hitch Hikers' Guide to the Galaxy)

- fact that they interact so rarely is what makes ν's so mysterious & their detection so challenging

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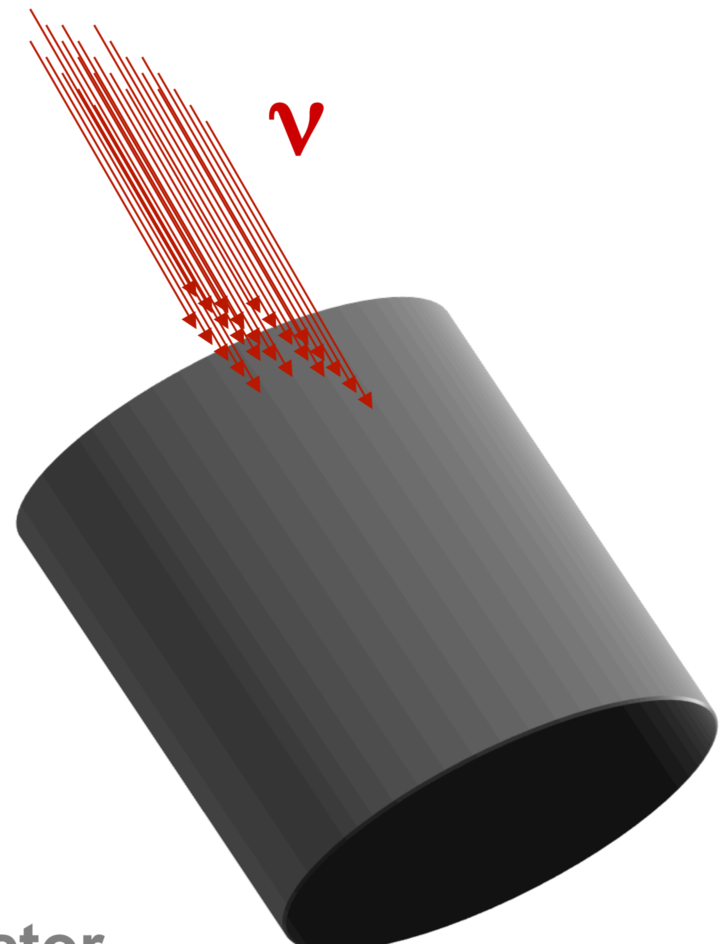
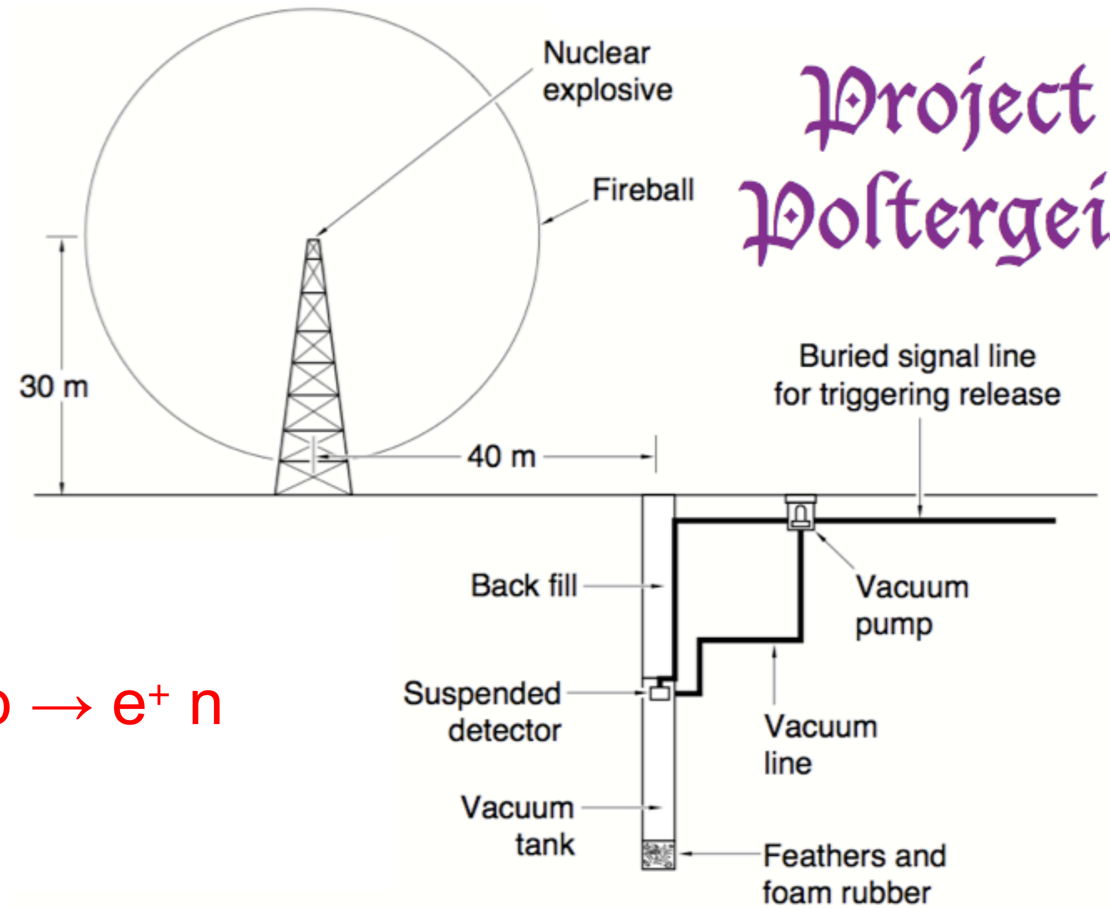


- fact that they interact so rarely is what makes ν's so mysterious & their detection so challenging

- to detect ν's, need a lot of **neutrinos** and lot of **detector**

Can We Detect Neutrinos?

25 years later ….



Project Poltergeist

Fred Reines

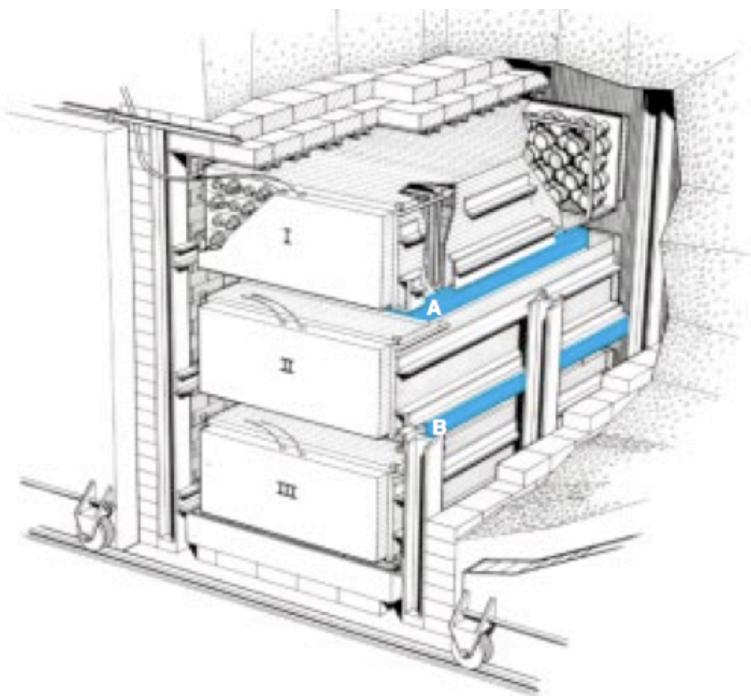
Clyde Cowan, Jr.

$\overline{\nu}_e\, p \rightarrow e^+\, n$

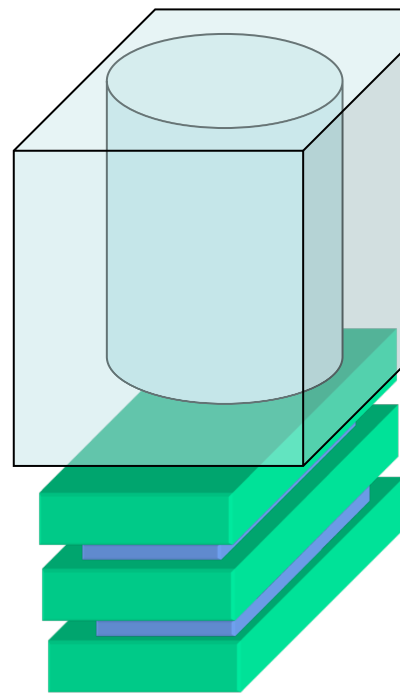
Surprise! Can Detect Neutrinos

eventually confirm that ν's exist by observing $\bar{\nu}_e$'s emitted by a nuclear reactor

$\bar{\nu}_e \, p \to e^+ \, n$ (IBD)



Savannah River nuclear reactor



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W E S T E R N   U N I O N

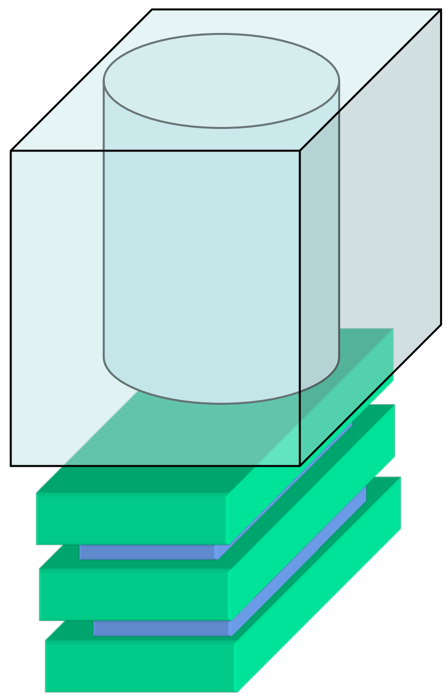
June 14, 1956

Dear Professor Pauli,

We are happy to inform you that we have definitely detected neutrinos . . .

Fred Reines
Clyde Cowan

Savannah River nuclear reactor

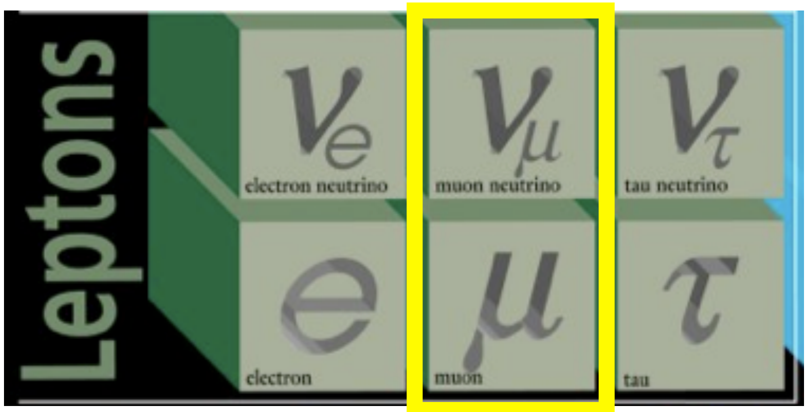


Fred Reines

Clyde Cowan, Jr.

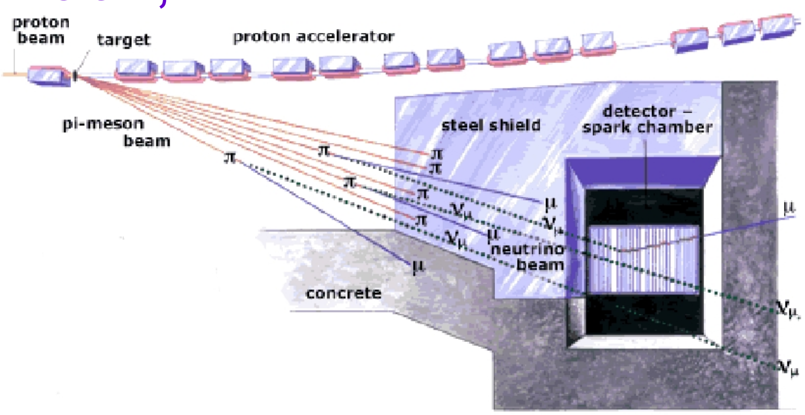
1995 Nobel prize

Surprise! There's More than One!



- discovered 2nd ν also using a man-made source

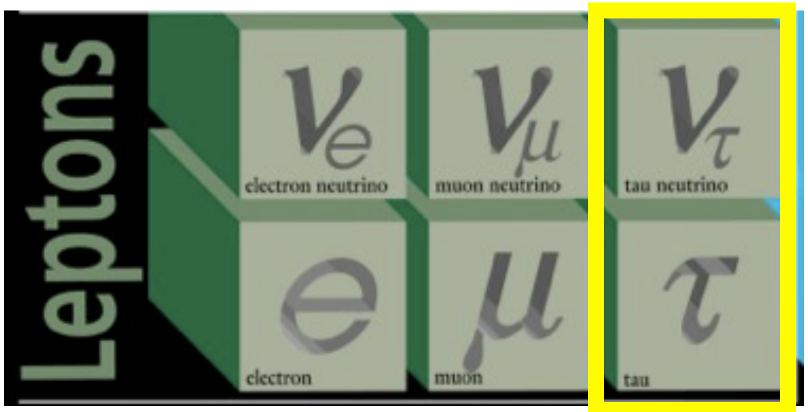
1962, BNL



(ν_μ's observed in accelerator environment)

1988 Nobel prize

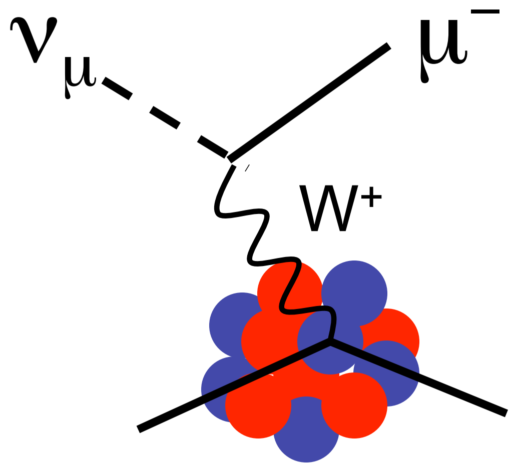
Surprise! There's More than One!



ν_τ not detected until 2000
(DONUT experiment at Fermilab)

- how do we know?

Neutrino Detection



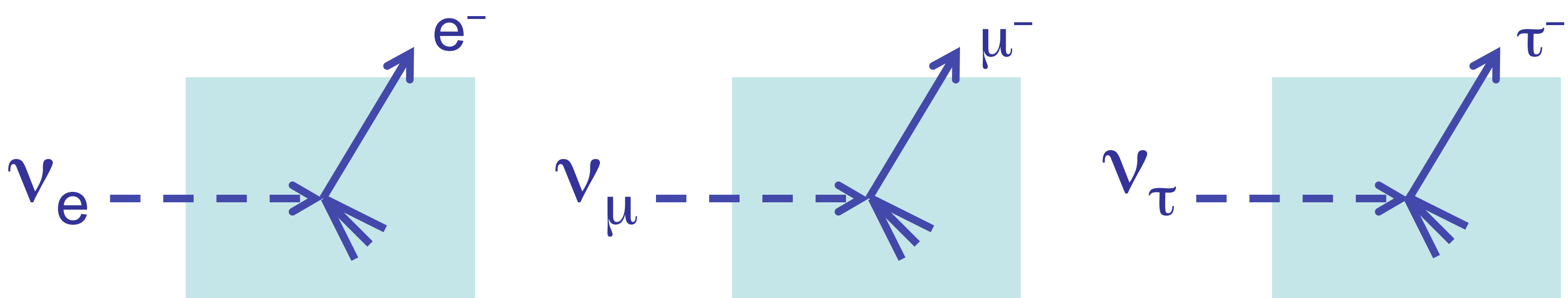
Charged Current (CC)

- neutrino in
- charged lepton out

$$\begin{pmatrix} \nu_e \rightarrow e \\ \nu_\mu \rightarrow \mu \\ \nu_\tau \rightarrow \tau \end{pmatrix}$$

this is how we detected neutrinos in the first place

- rely on indirect detection to "see" neutrinos
- transforms an initial state ν into its charged lepton partner



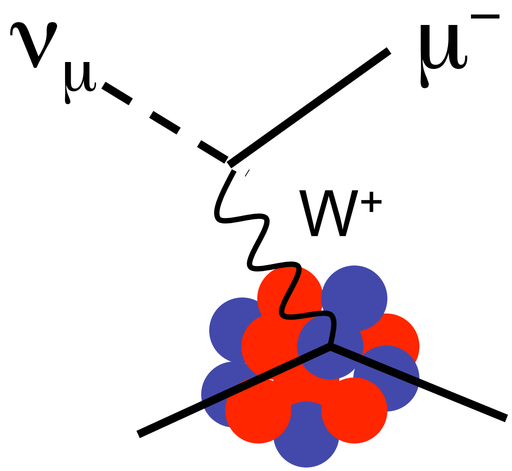
each leaves its own recognizable pattern

Surprise! Two Types of Interactions

• around this same time, Glashow-Weinberg-Salam predict a new type of ν interaction (where particles maintain their identities)

Glashow, Salam, Weinberg sharing the Nobel Prize, 1979

Surprise! Two Types of Interactions



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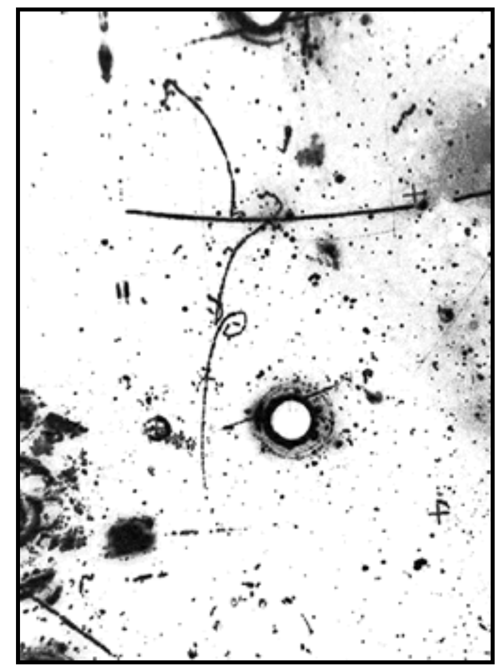
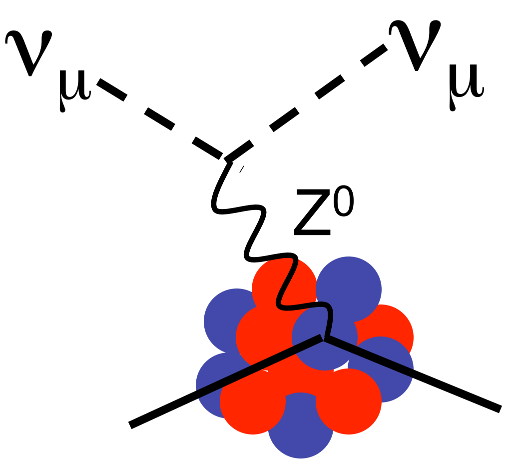




Neutral Current (NC)
- neutrino in
- neutrino out

- famous ν interaction
- seen in 1973 (Europe, U.S.)
- 1979 Nobel prize

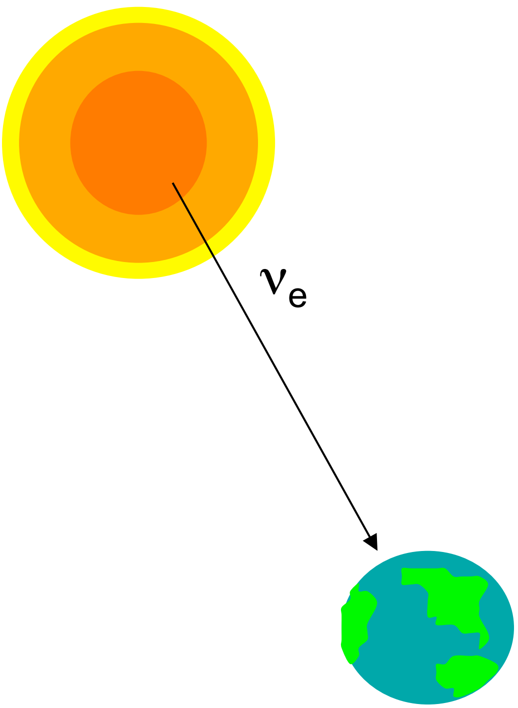
(studying this further was subject of my thesis)

Surprise! Neutrinos Oscillate

astonishing sequence of experiments revealed that neutrinos oscillate … observation shook the ν community

Solar

$\nu_e \rightarrow \nu_{\mu,\tau}$



1960's: Ray Davis builds first large scale detector to look for ν's from the sun

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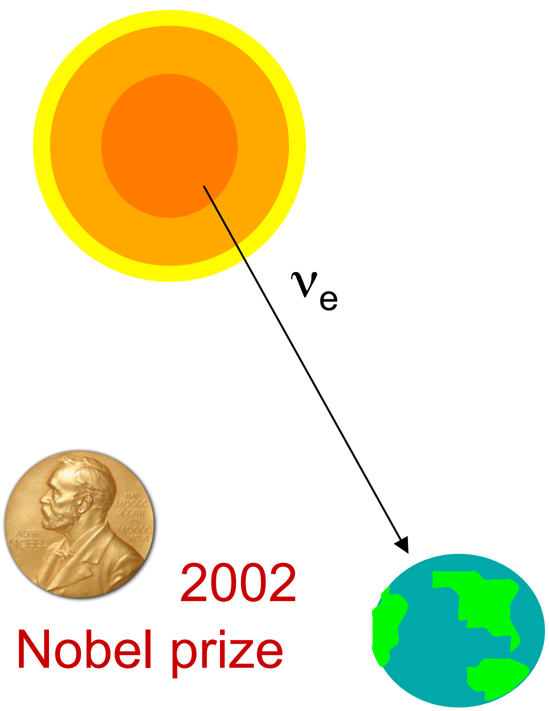

2002
Nobel prize

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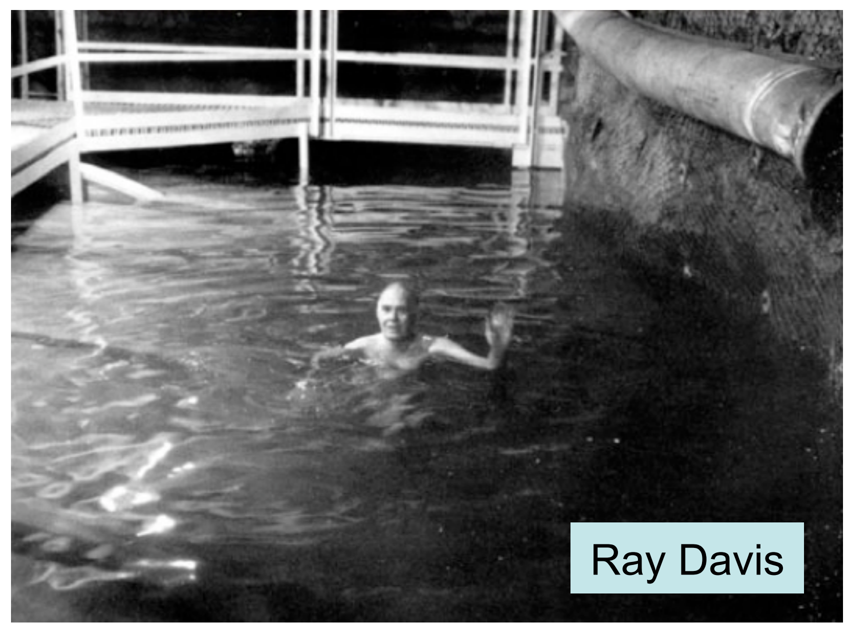

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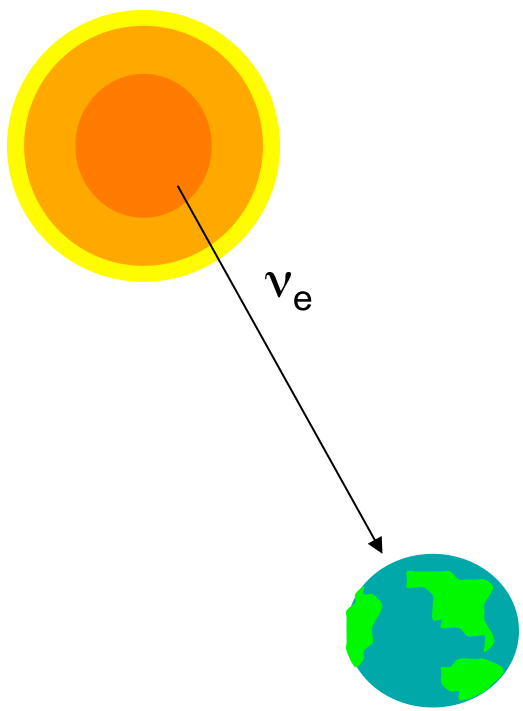

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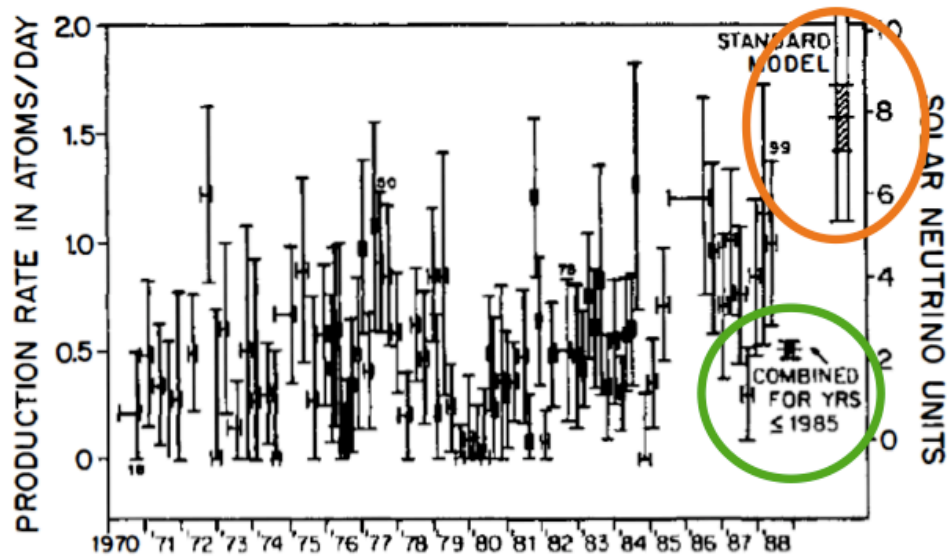

"solar neutrino problem"

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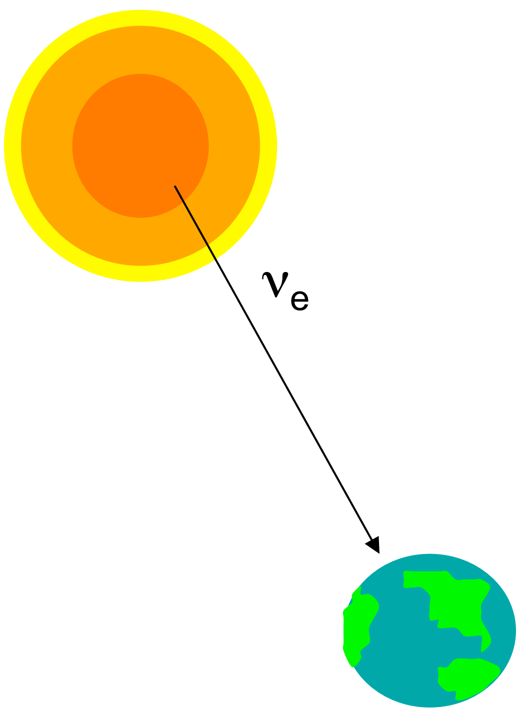
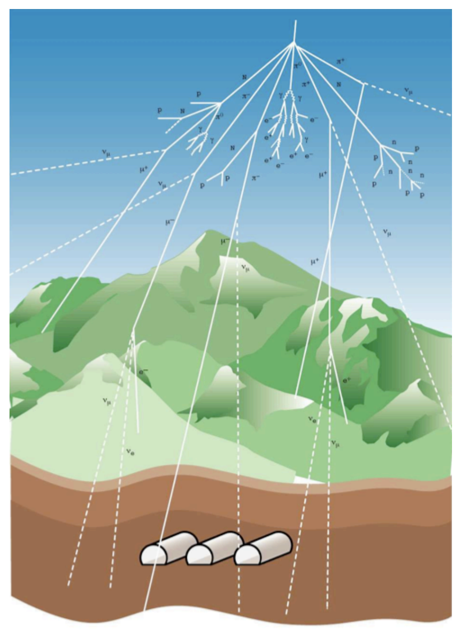
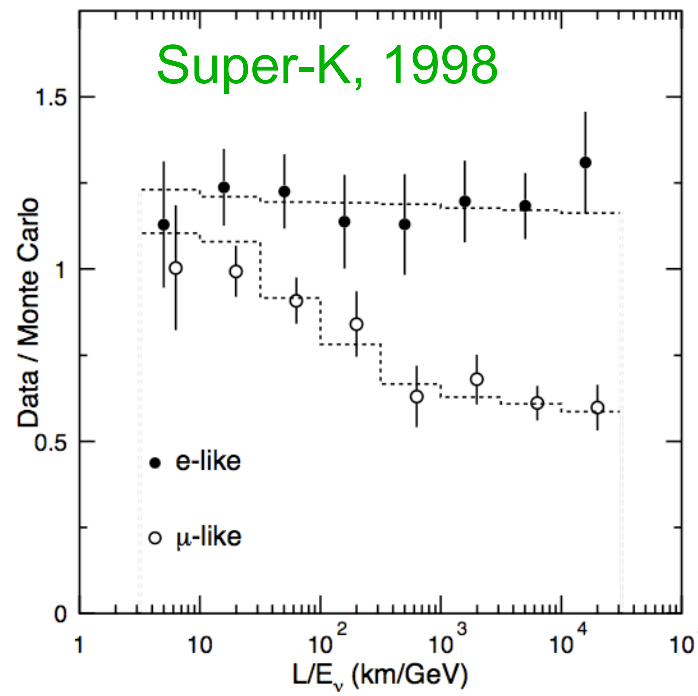


Atmospheric

$\nu_\mu \rightarrow \nu_\tau$





implication: ν's have mass!

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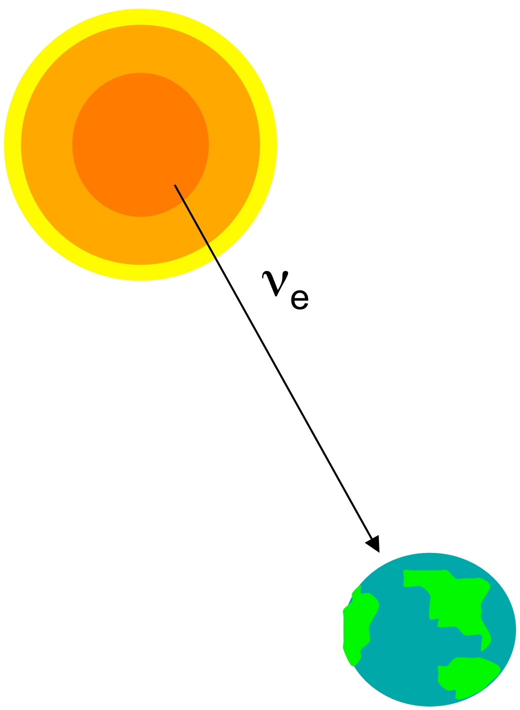

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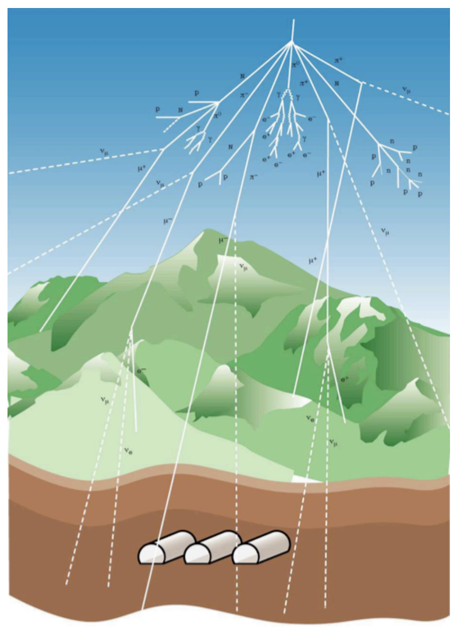

ir .

"All the News That's Fit to Print"

The New York

VOL. CXLVII . . . . No. 51,179

FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

Detecting Neutrinos

1. Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .
2. . . . and collide with other particles . . .
3. . . . producing a cone-shaped flash of light.
4. The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

LIGHT

LIGHT AMPLIFIER

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times

OKLAHOMA BLAST BRINGS LIFE TERM FOR TERRY NICHOLS

'ENEMY OF CONSTITUTION'

Judge Denounces Conspiracy and Hears From the Victims of a Terrifying Ordeal

By JO THOMAS

DENVER, June 4 — Calling him "an enemy of the Constitution," a Federal judge today sentenced Terry L. Nichols to life in prison without the possibility of parole for conspiring to bomb the Oklahoma City Federal Building, the deadliest terrorist attack ever on American soil.

In passing sentence after hearing from survivors of the blast and relatives of some of the 168 people who died in it, the judge, Richard P. Matsch of Federal District Court, said, "This was not a murder case."

He added: "It is a crime and the victims have spoken eloquently here. But it is not a crime as to them so much as it is a crime against the Constitution of the United States. That's the victim."

Last December, Mr. Nichols was convicted of conspiring with Timothy J. McVeigh to use a weapon of mass destruction in the April 19, 1995, bombing of the Alfred P. Murrah Federal Building, but was acquitted of Federal murder charges in the deaths of eight Federal agents who died. Mr. Nichols was found guilty of involuntary manslaughter in those deaths and today was given the maximum sentence of six years in prison for each, to run concurrently with his life sentence. He was also acquitted of actually committing the bombing.

While the conspiracy charge carried a possible death sentence, the jurors need to vote unanimously for such punishment, and they could not do so. The sentencing then fell to Judge Matsch.

Bajram Curri, in no
Yugoslavia in three

Refugees A Bitte

PADESH, Albania,
dent Slobodan Milose
via has unleashed th
tary operation in the
the end of the war in
thousands of ethnic
the border area wi
reducing their villag
At least 10,000
streamed through

NY Times, June 1998

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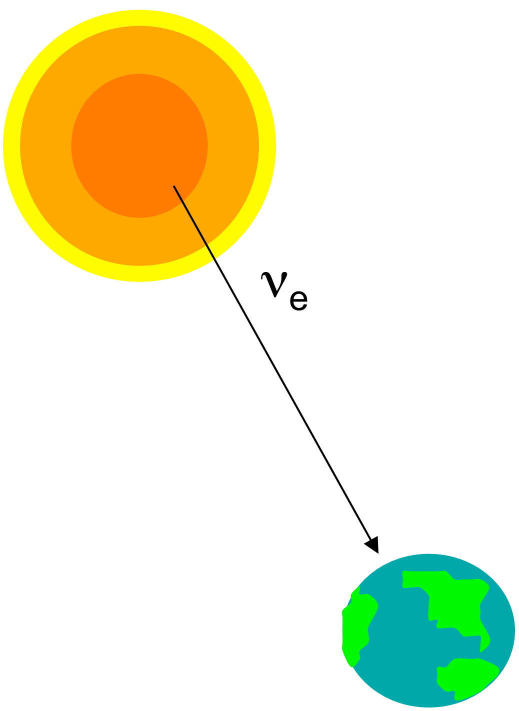
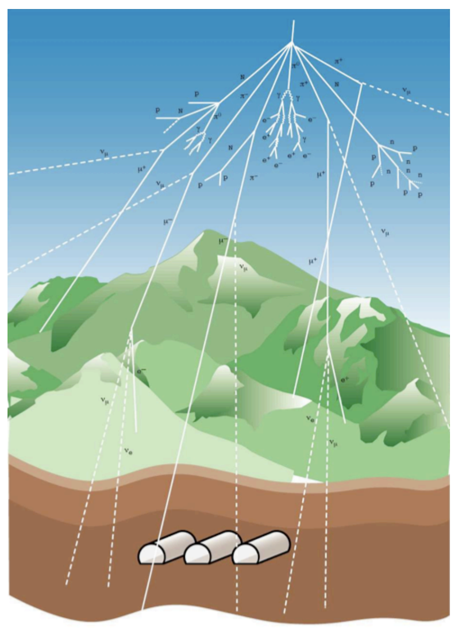
Solar

$\nu_e \rightarrow \nu_{\mu,\tau}$



Atmospheric

$\nu_\mu \rightarrow \nu_\tau$



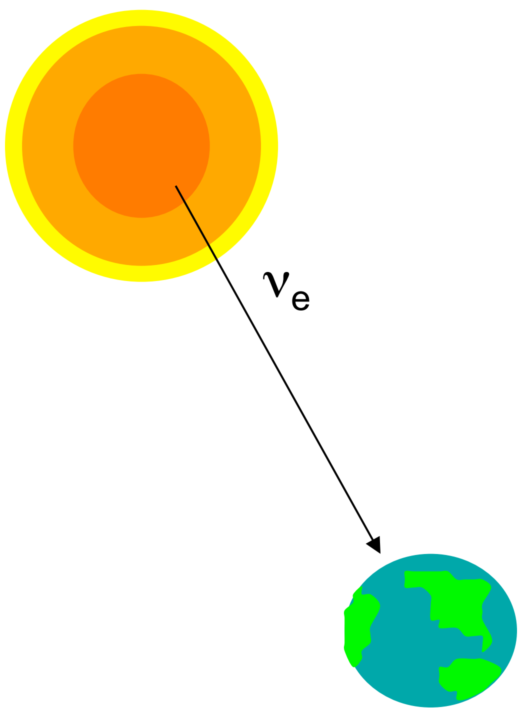
- has since been confirmed by multiple ν experiments
- replicated with man-made sources (reactor, accelerator)

Surprise! Neutrinos Oscillate

astonishing sequence of experiments revealed that neutrinos oscillate … observation shook the ν community

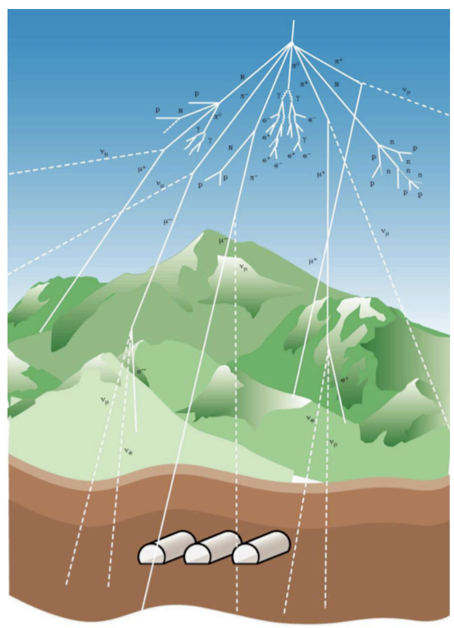
Solar

$\nu_e \rightarrow \nu_{\mu,\tau}$



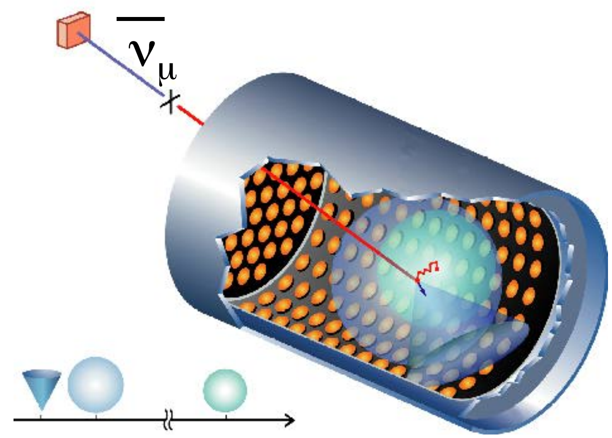
Atmospheric

$\nu_\mu \rightarrow \nu_\tau$



LSND

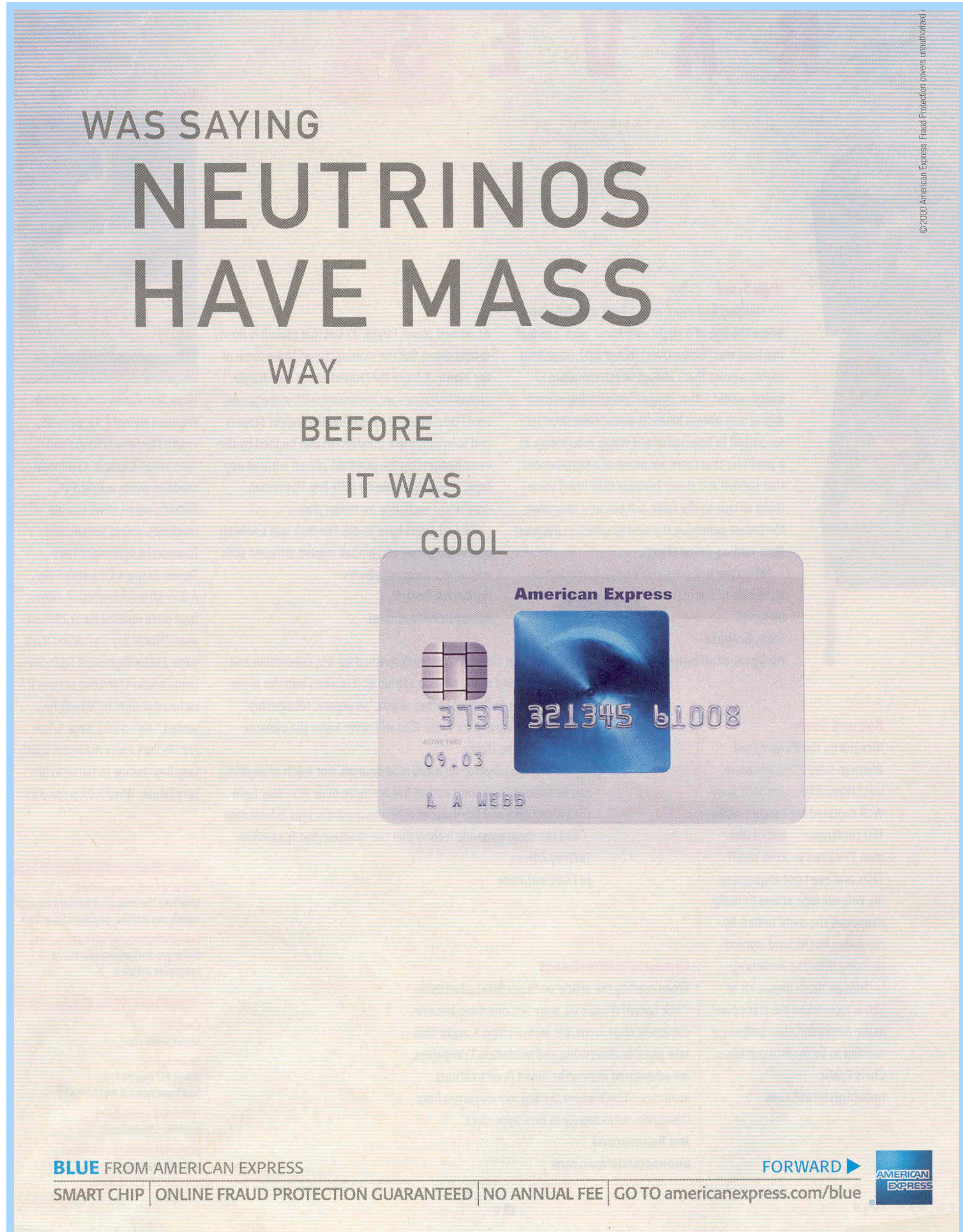
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



we'll come back to this

… but apparently …

American Express
was the first to discover?



… apparently they knew
but just didn't tell us

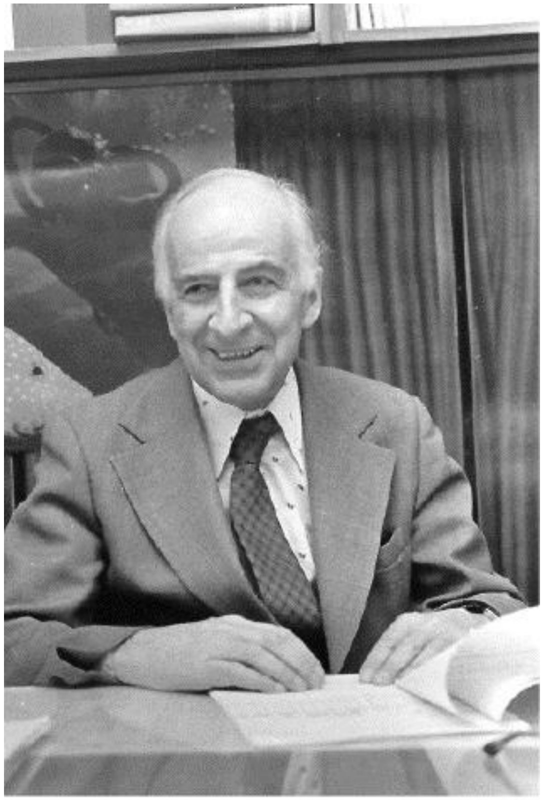
Neutrinos Oscillations

(first suggested by Pontecorvo, 1957)

- one of the most exciting developments in ν physics in the past ~10 years …

- neutrinos oscillate from one type to another

$$\nu_1 \rightarrow \nu_2$$



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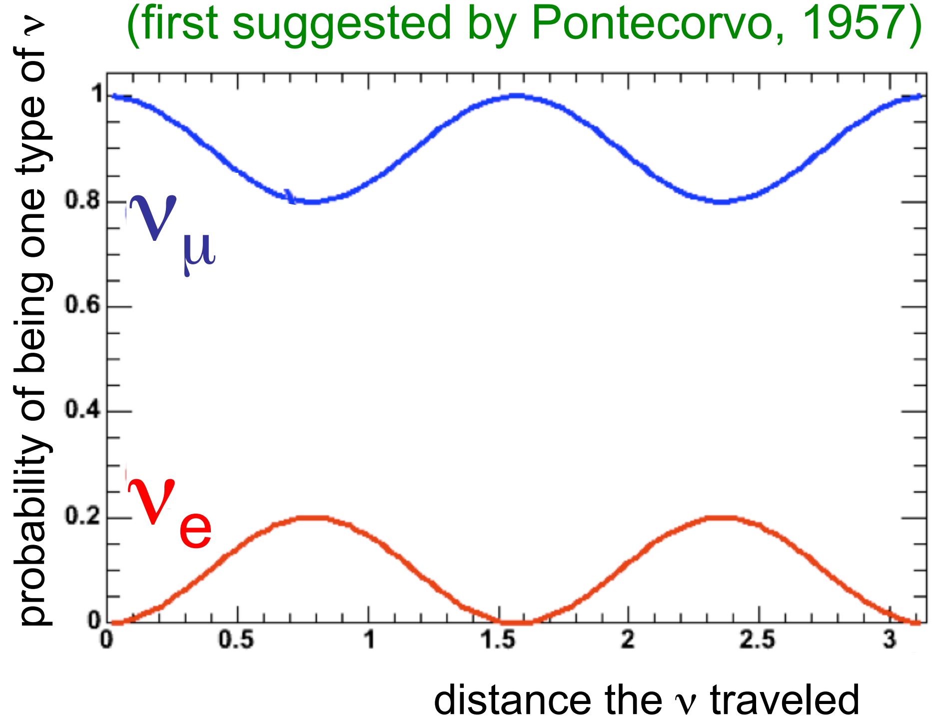

- both ν disappearance and appearance

Neutrinos Oscillations

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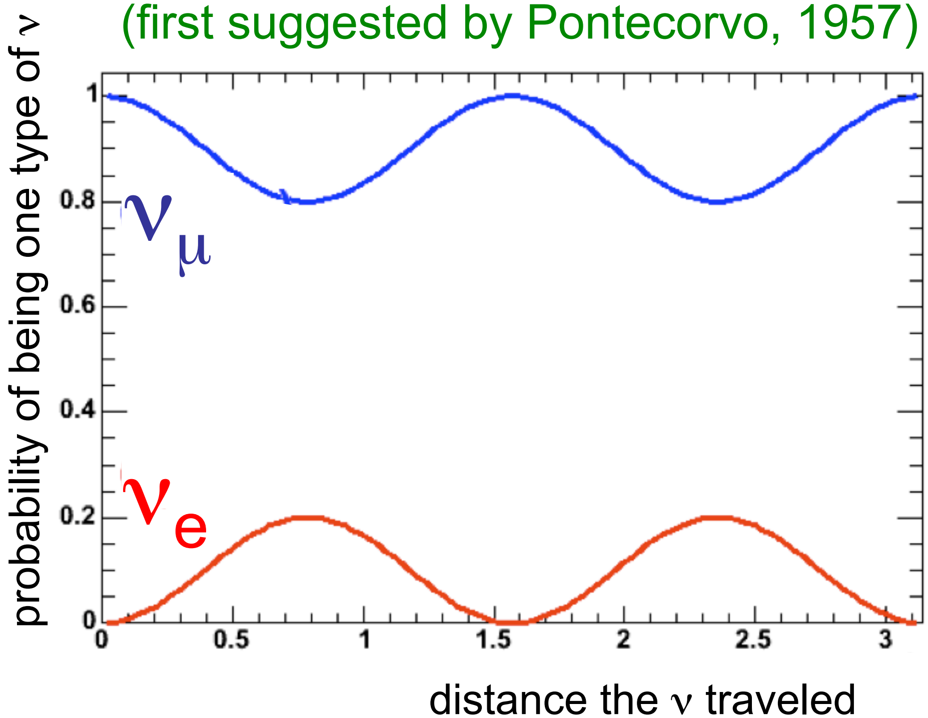

$$P_{12} = \sin^2 2\theta \, \sin^2 \left(\frac{1.27 \, \Delta m^2 \, L}{E} \right)$$

- simple equation tells you probability that a ν starting off life as one type can be observed later as another type

Neutrinos Oscillations

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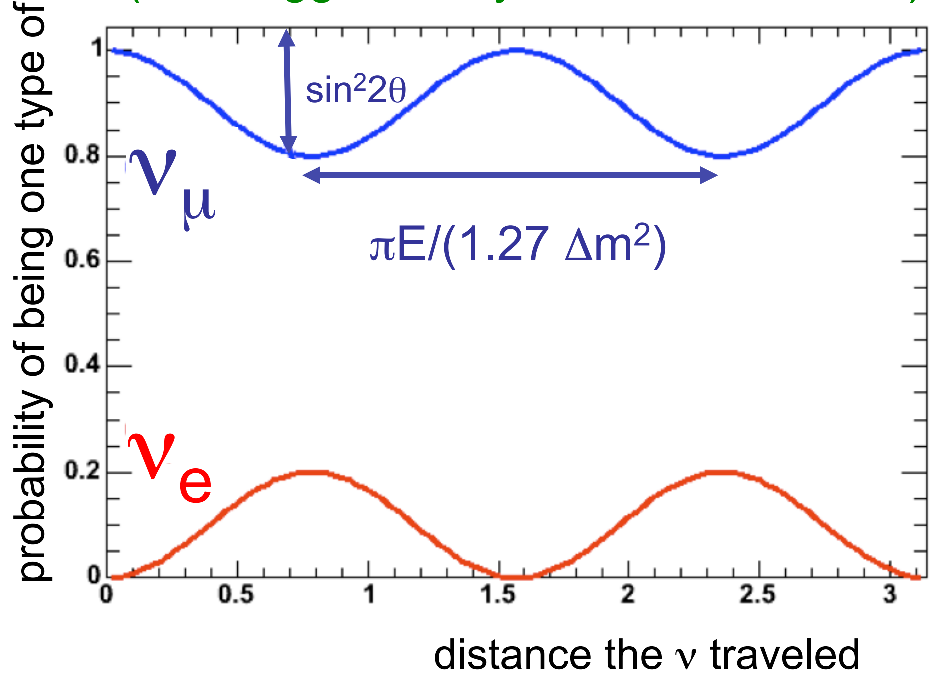

$$P_{12} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\,\Delta m^2\, L}{E}\right)$$

L = distance ν has traveled
E = energy of the ν

$\sin^2 2\theta$ = amplitude
Δm^2 = mass difference

Neutrinos Oscillations

- one of the most exciting developments in ν physics in the past ~10 years …

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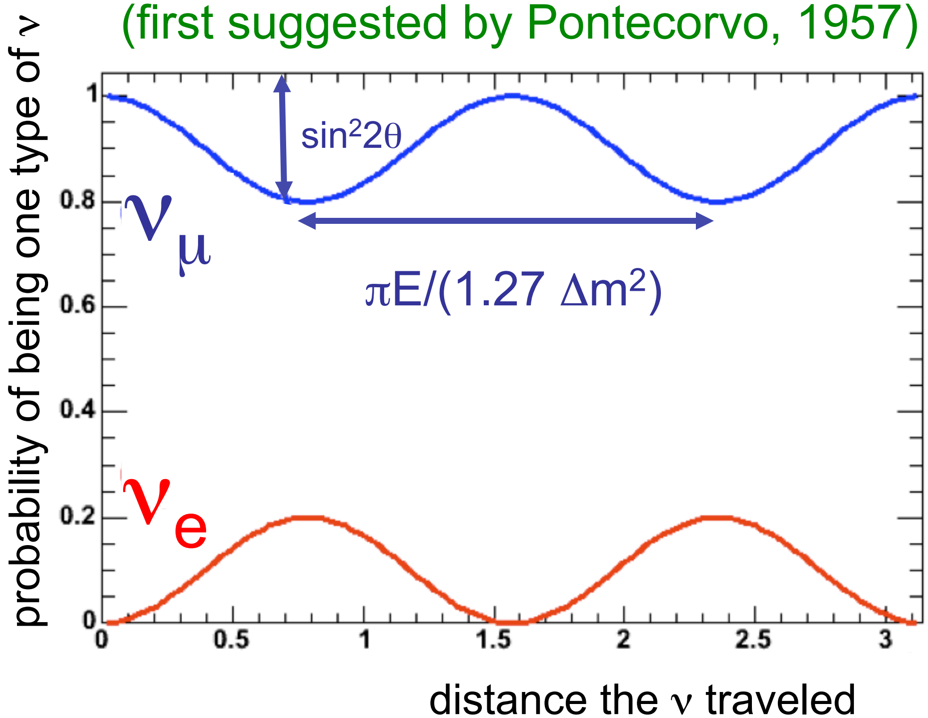
(first suggested by Pontecorvo, 1957)



$$P_{12} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\,\Delta m^2\,L}{E}\right)$$

"At present this is highly speculative- there is no experimental evidence for neutrino oscillations…" D.J. Griffiths (1995), *Introduction to Quantum Mechanics*

Neutrinos Oscillations

- one of the most exciting developments in ν physics in the past ~10 years …

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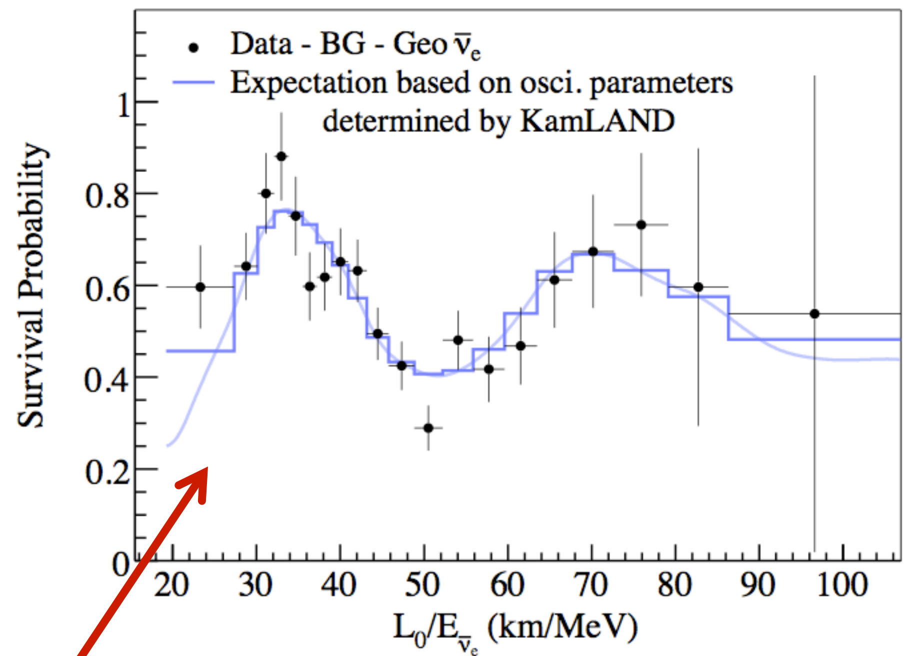
$$P_{12} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

Abe *et al.*, PRL 100, 221803 (2008)



- using same reaction, similar detection technique as Reines & Cowan … but 50 years later!

Current Landscape

- have observed **three** different oscillation signals so far …

atmospheric oscillations

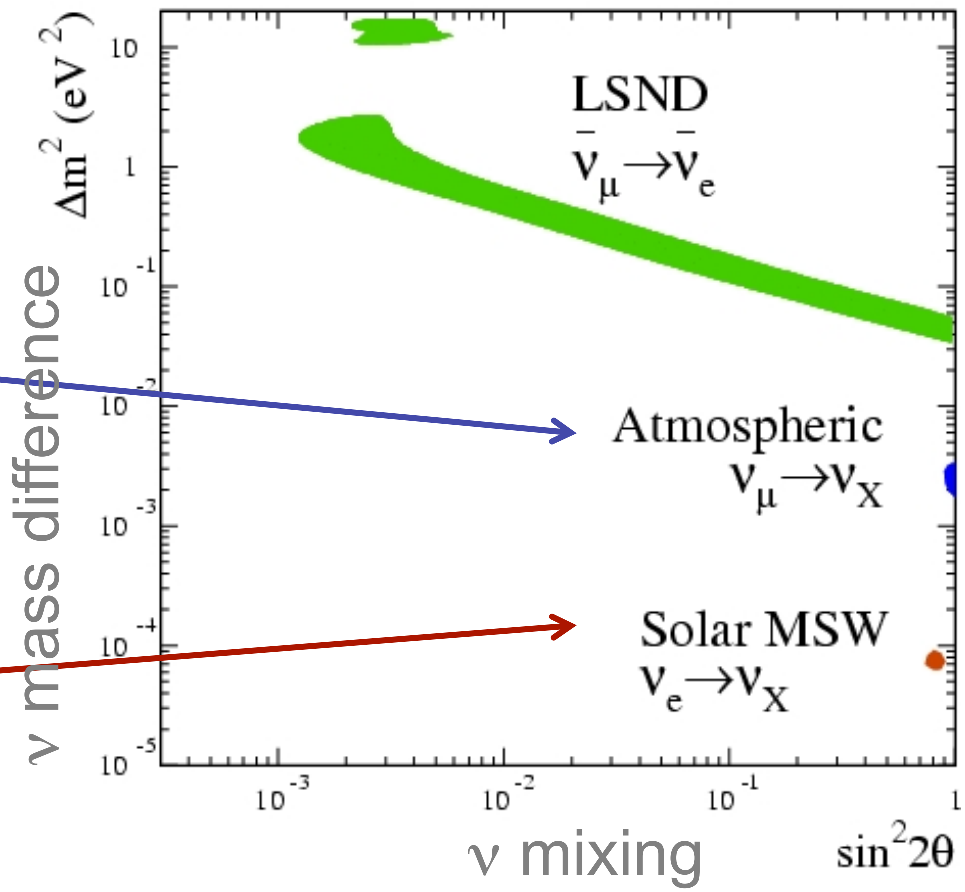
$\Delta m^2 \sim 10^{-3}$ eV^2

$\theta \sim 45^0$

solar oscillations

$\Delta m^2 \sim 10^{-5}$ eV^2

$\theta \sim 34^0$



first, neutrino mixing is **weird**

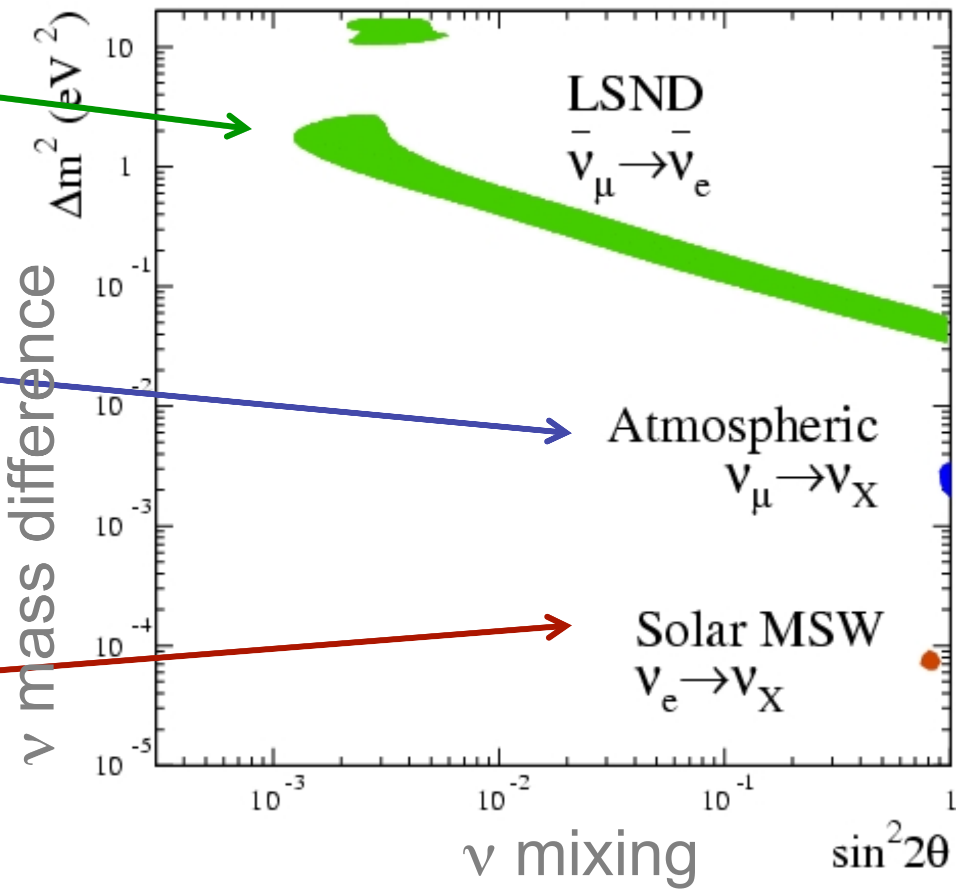
Current Landscape

- have observed **three** different oscillation signals so far …

LSND
$\Delta m^2 \sim 1\ eV^2$
$\theta \sim 2^0$

atmospheric oscillations
$\Delta m^2 \sim 10^{-3}\ eV^2$
$\theta \sim 45^0$

solar oscillations
$\Delta m^2 \sim 10^{-5}\ eV^2$
$\theta \sim 34^0$



3 signals, so what's the problem with this?

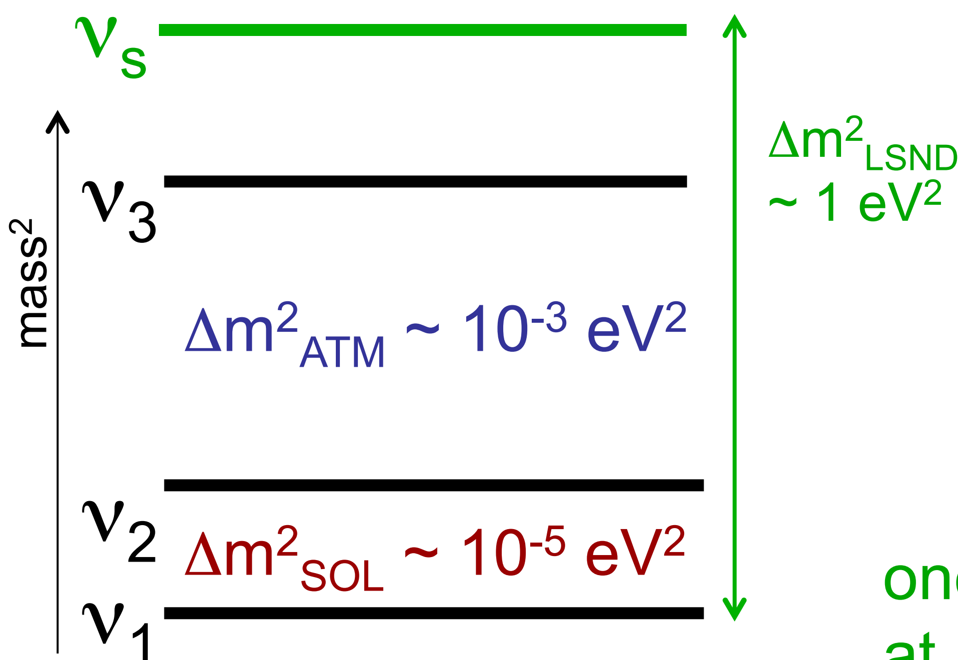
Too Many Signals

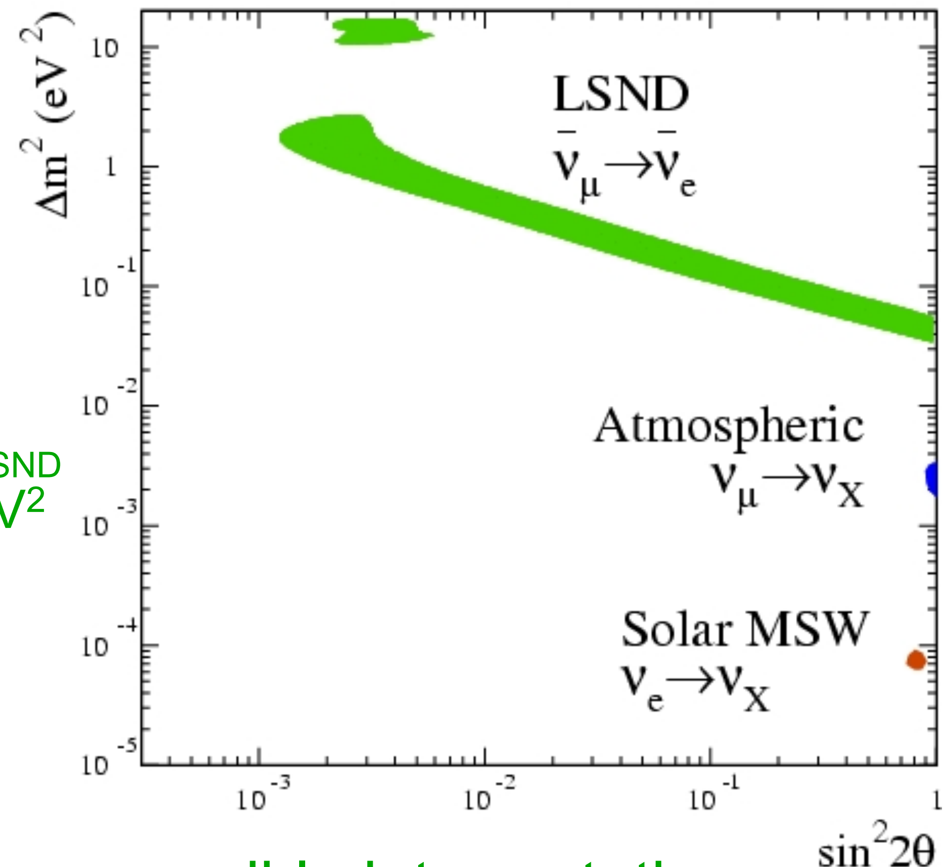
- have observed **three** different oscillation signals so far …

- that's too many Δm^2 regions!

  3 ν's implies 2 indep mass scales:

  $(10^{-5} + 10^{-3} \neq 1)$

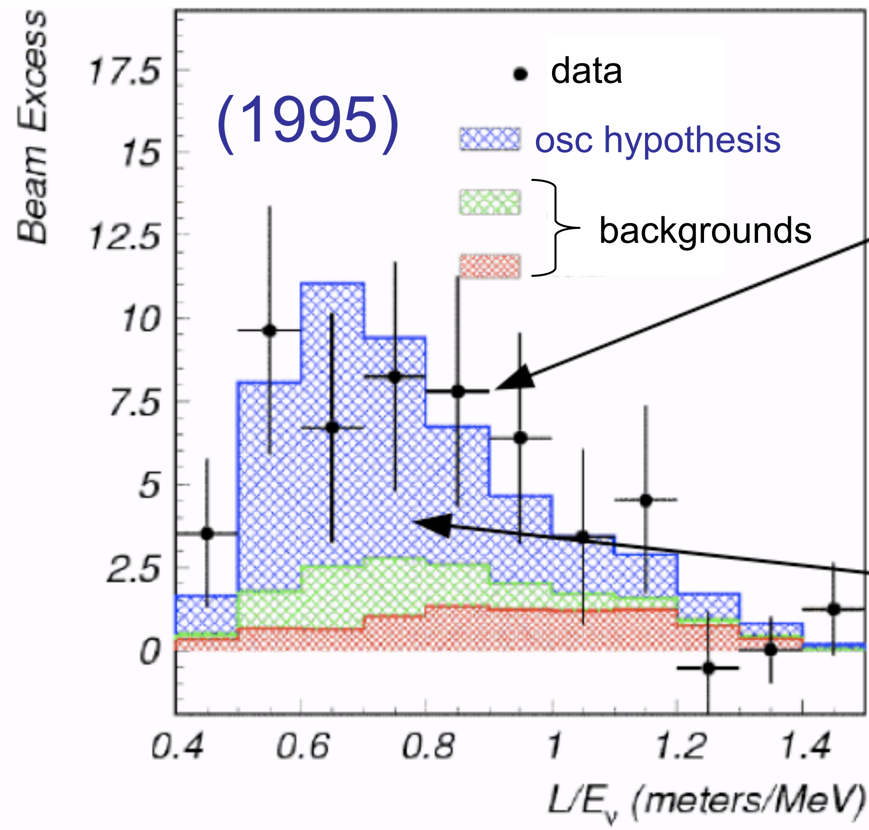


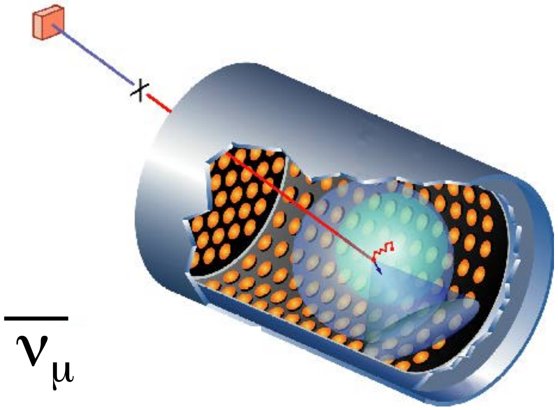


one possible interpretation:
at least one extra ν (sterile ν)

LSND

Liquid **S**cintillator **N**eutrino **D**etector





$\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu}$

observed excess of $\overline{\nu_e}$ in a $\overline{\nu_\mu}$ beam (3.8σ significance)

could be interpreted as $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ oscillations with oscillation probability:

$$P(\overline{\nu_\mu} \rightarrow \overline{\nu_e}) = \sin^2 2\theta \sin^2\left(\frac{1.27\, \Delta m^2\, L}{E}\right) = 0.26\%$$

Test This

- run a new experiment at same L/E
  - want sensitivity to the same ν oscillations as LSND

$$\boxed{P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2\left(\frac{1.27\,\Delta m^2\, \mathbf{L}}{\mathbf{E}}\right)}$$

- **that's MiniBooNE**! designed to look for $\nu_\mu \rightarrow \nu_e$
  - both **L**, **E** are 10x larger
    - different signal signature & backgrounds
    - different systematic uncertainties
    - higher statistics

independent check

MiniBooNE

Mini Booster Neutrino Experiment

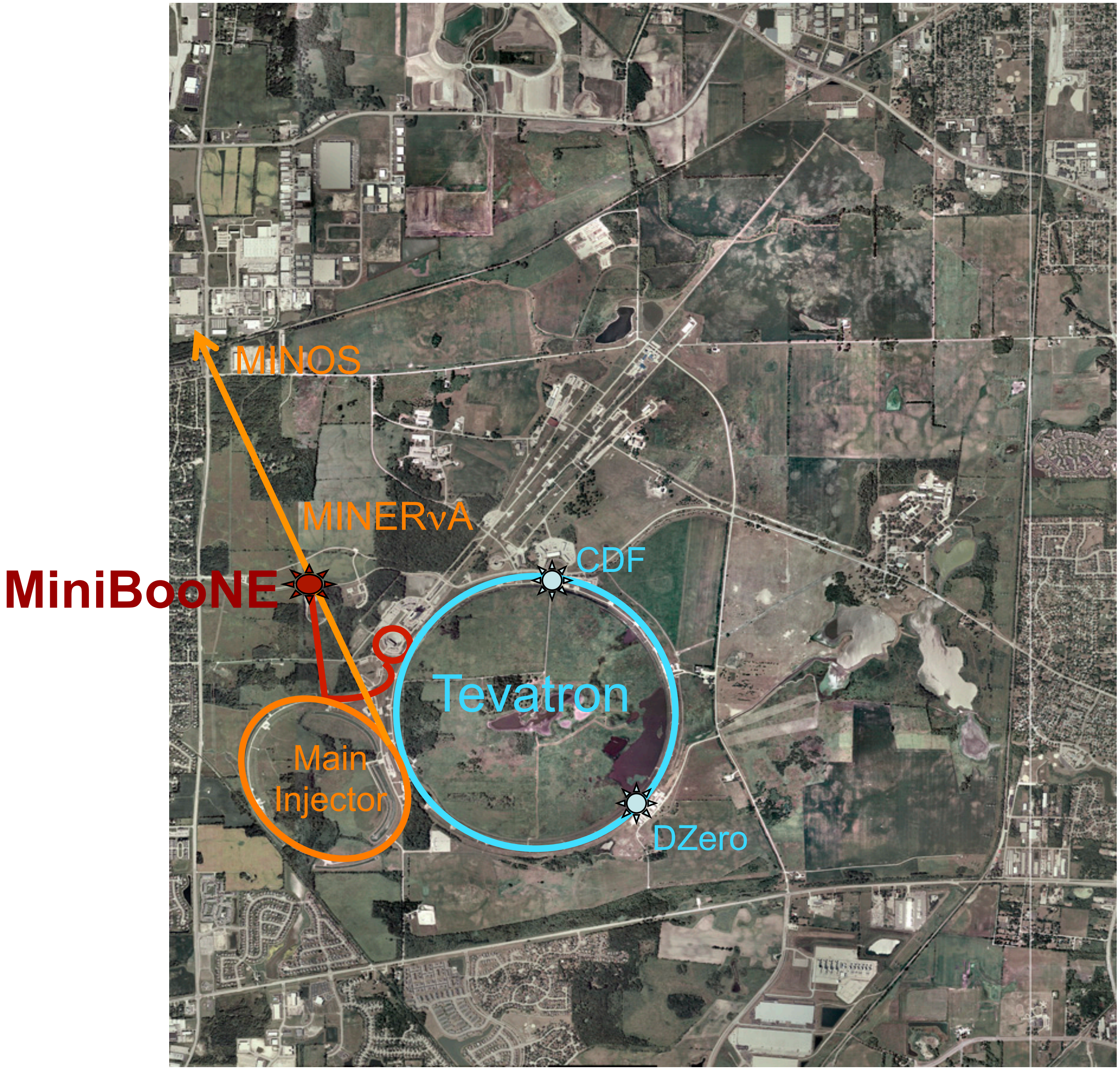
- 85 physicists
- 18 institutions

(collaboration may be larger than it appears)

A. A. Aguilar-Arevalo[13], C. E. Anderson[18], A. O. Bazarko[15], S. J. Brice[7], B. C. Brown[7], L. Bugel[5], J. Cao[14], L. Coney[5], J. M. Conrad[12], D. C. Cox[9], A. Curioni[18], Z. Djurcic[5], D. A. Finley[7], B. T. Fleming[18], R. Ford[7], F. G. Garcia[7], G. T. Garvey[10], J. Grange[8], C. Green[7,10], J. A. Green[9,10], T. L. Hart[4], E. Hawker[3,10], R. Imlay[11], R. A. Johnson[3], G. Karagiorgi[12], P. Kasper[7], T. Katori[9,12], T. Kobilarcik[7], I. Kourbanis[7], S. Koutsoliotas[2], E. M. Laird[15], S. K. Linden[18],J. M. Link[17], Y. Liu[14], Y. Liu[1], W. C. Louis[10], K. B. M. Mahn[5], W. Marsh[7], C. Mauger[10], V. T. McGary[12], G. McGregor[10], W. Metcalf[11], P. D. Meyers[15], F. Mills[7], G. B. Mills[10], J. Monroe[5], C. D. Moore[7], J. Mousseau[8], R. H. Nelson[4], P. Nienaber[16], J. A. Nowak[11], B. Osmanov[8], S. Ouedraogo[11], R. B. Patterson[15], Z. Pavlovic[10], D. Perevalov[1], C. C. Polly[7], E. Prebys[7], J. L. Raaf[3], H. Ray[8,10], B. P. Roe[14], A. D. Russell[7], V. Sandberg[10], R. Schirato[10], D. Schmitz[5], M. H. Shaevitz[5], F. C. Shoemaker[15*], D. Smith[6], M. Soderberg[18], M. Sorel[5†], P. Spentzouris[7], J. Spitz[18], I. Stancu[1], R. J. Stefanski[7], M. Sung[11], H. A. Tanaka[15], R. Tayloe[9], M. Tzanov[4], R. G. Van de Water[10], M. O. Wascko[11‡], D. H. White[10], M. J. Wilking[4], H. J. Yang[14], G. P. Zeller[7], E. D. Zimmerman[4]

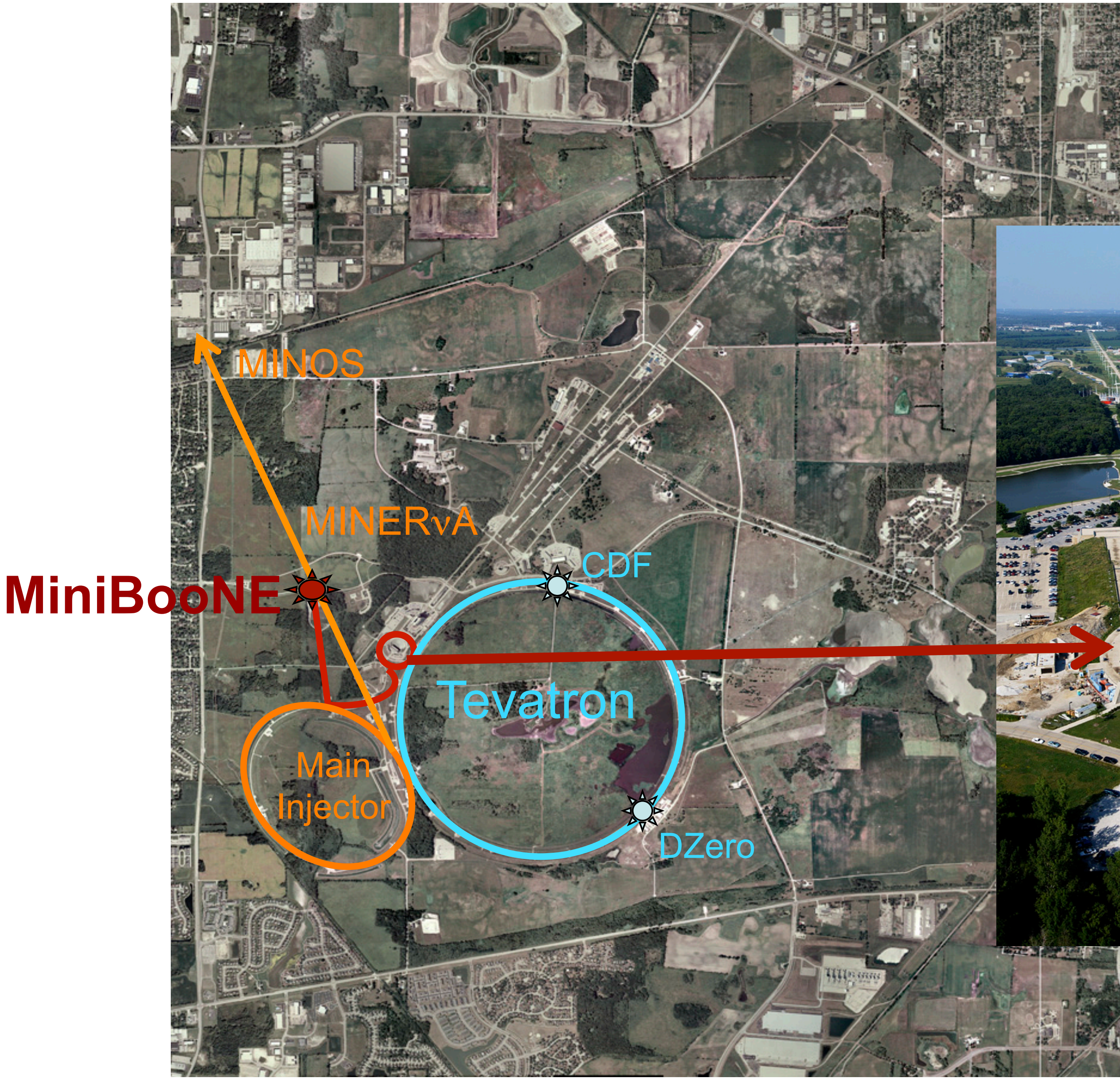
Fermilab

Batavia, IL



Fermilab

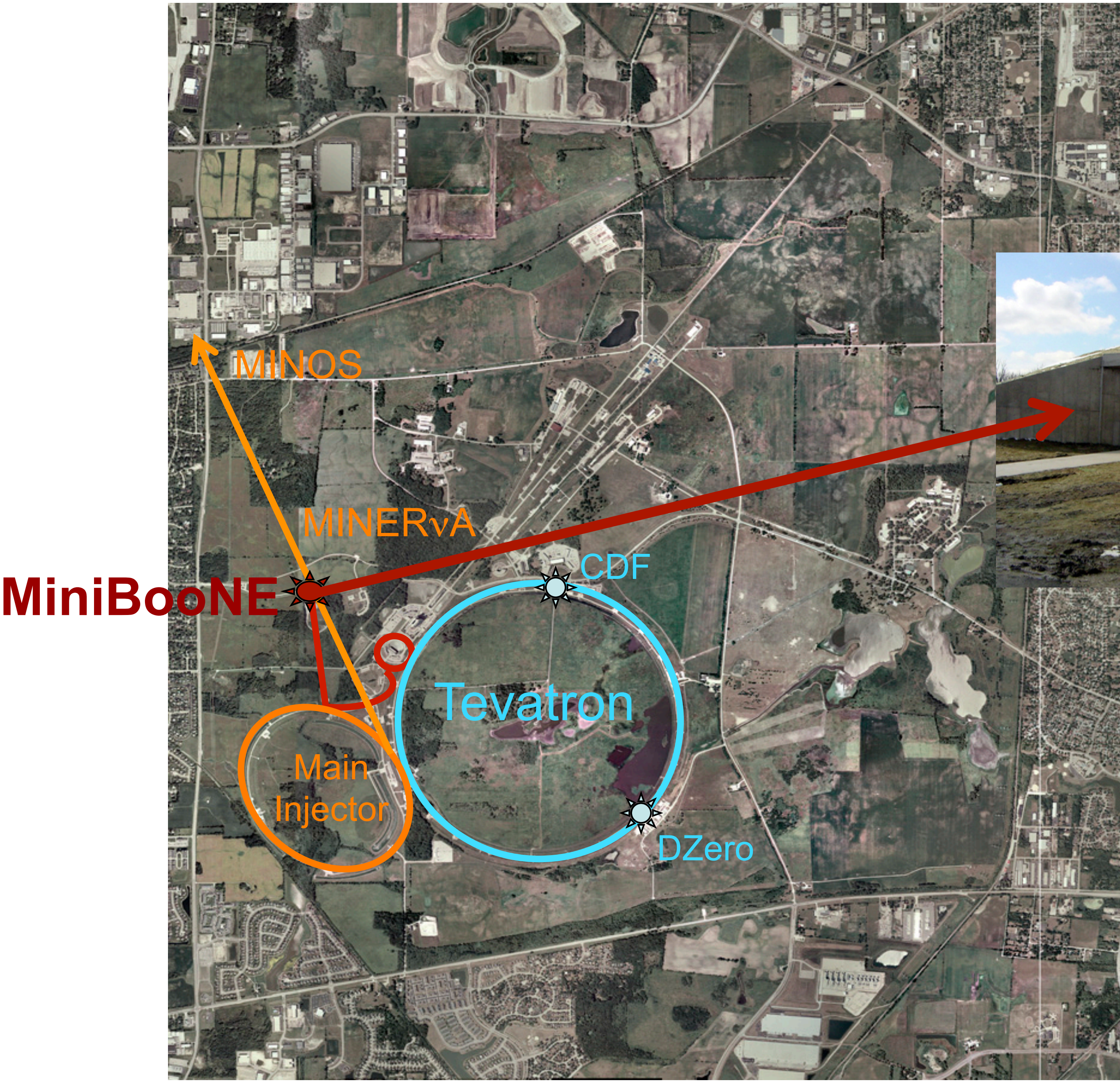
Batavia, IL



Fermilab Booster

Fermilab

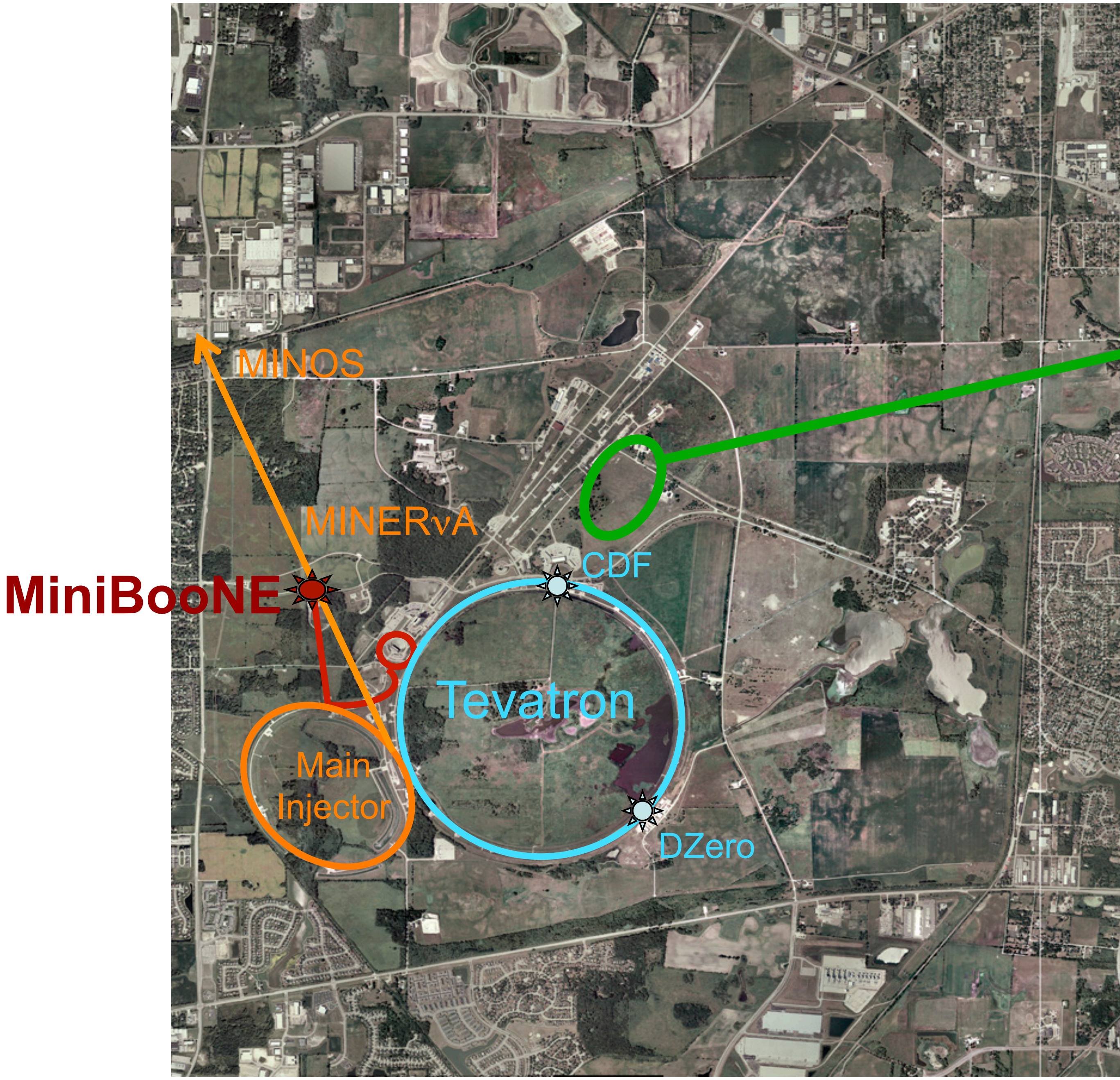
Batavia, IL



MiniBooNE detector hall

Fermilab

Batavia, IL

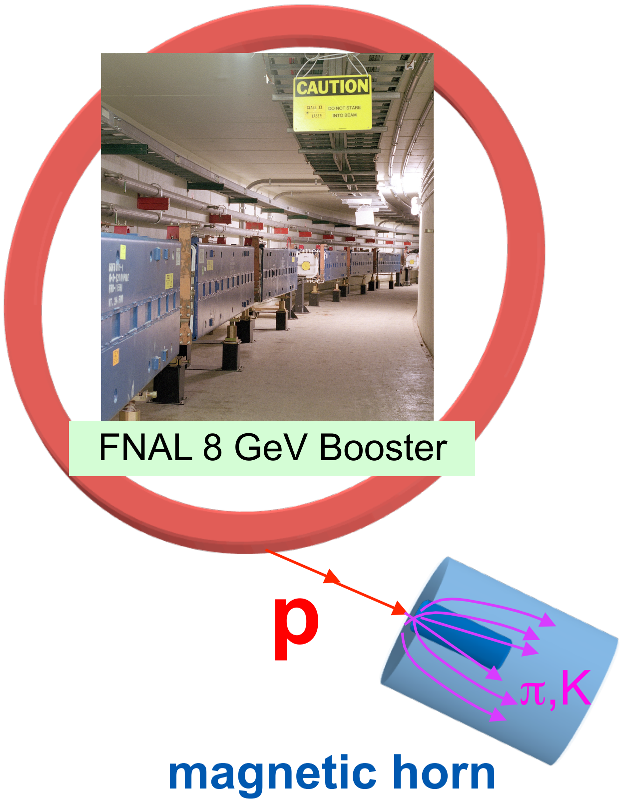


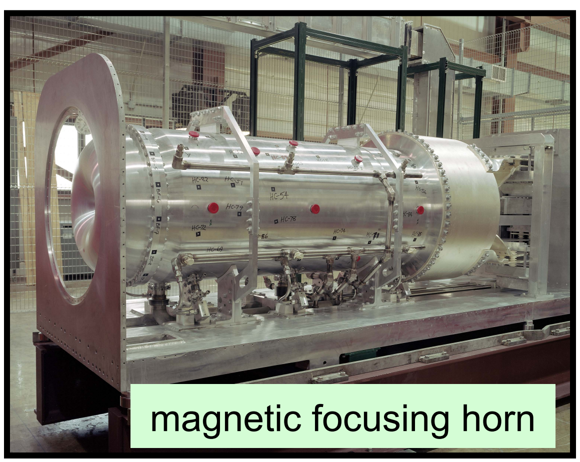
Fermilab bison

MiniBooNE
ν Beam

How we turn protons
into neutrinos

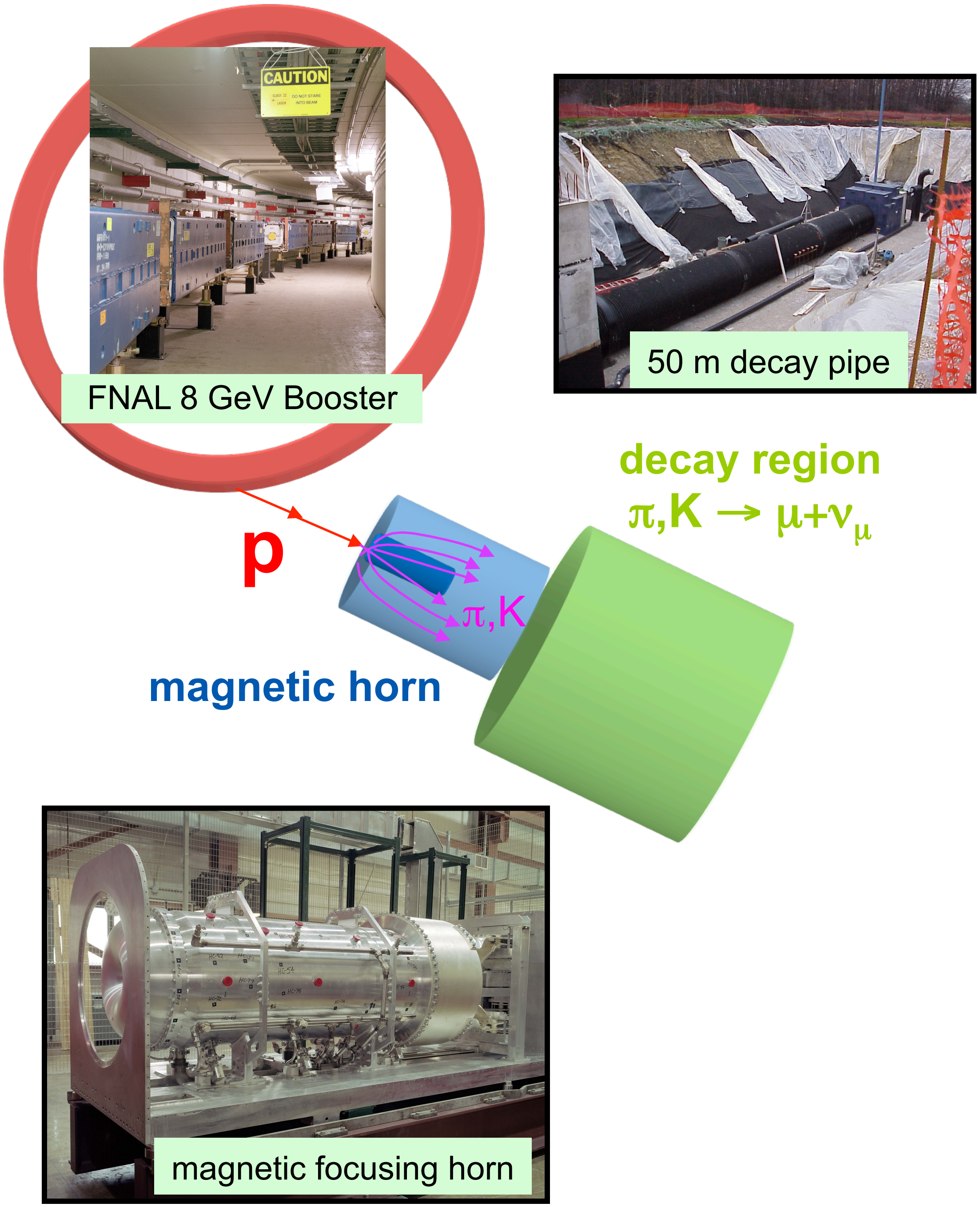
MiniBooNE
ν Beam



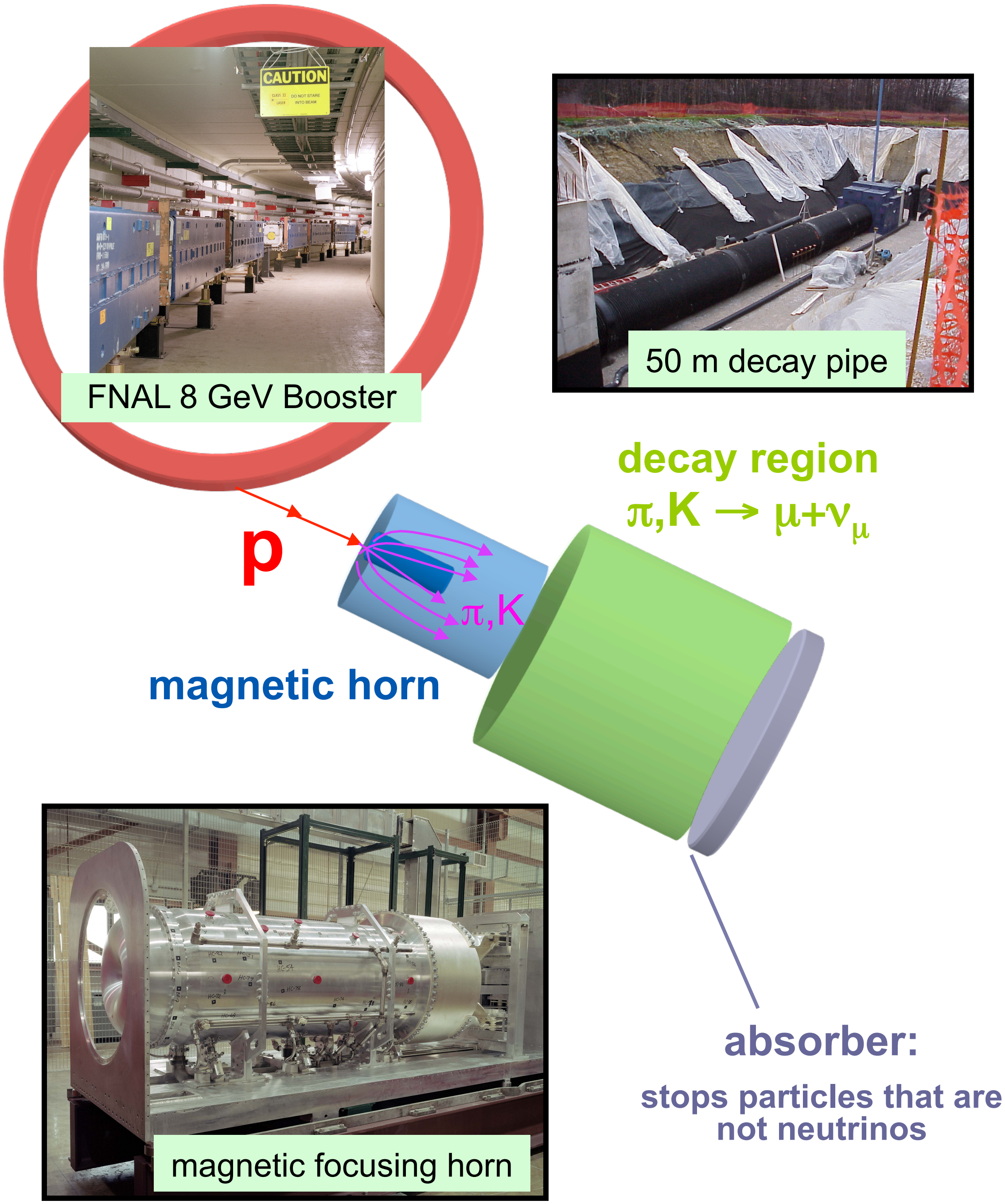


- run 174kA current through horn
- record number of pulses (260 million!)
- can change polarity of horn (ν or $\bar{\nu}$ mode)

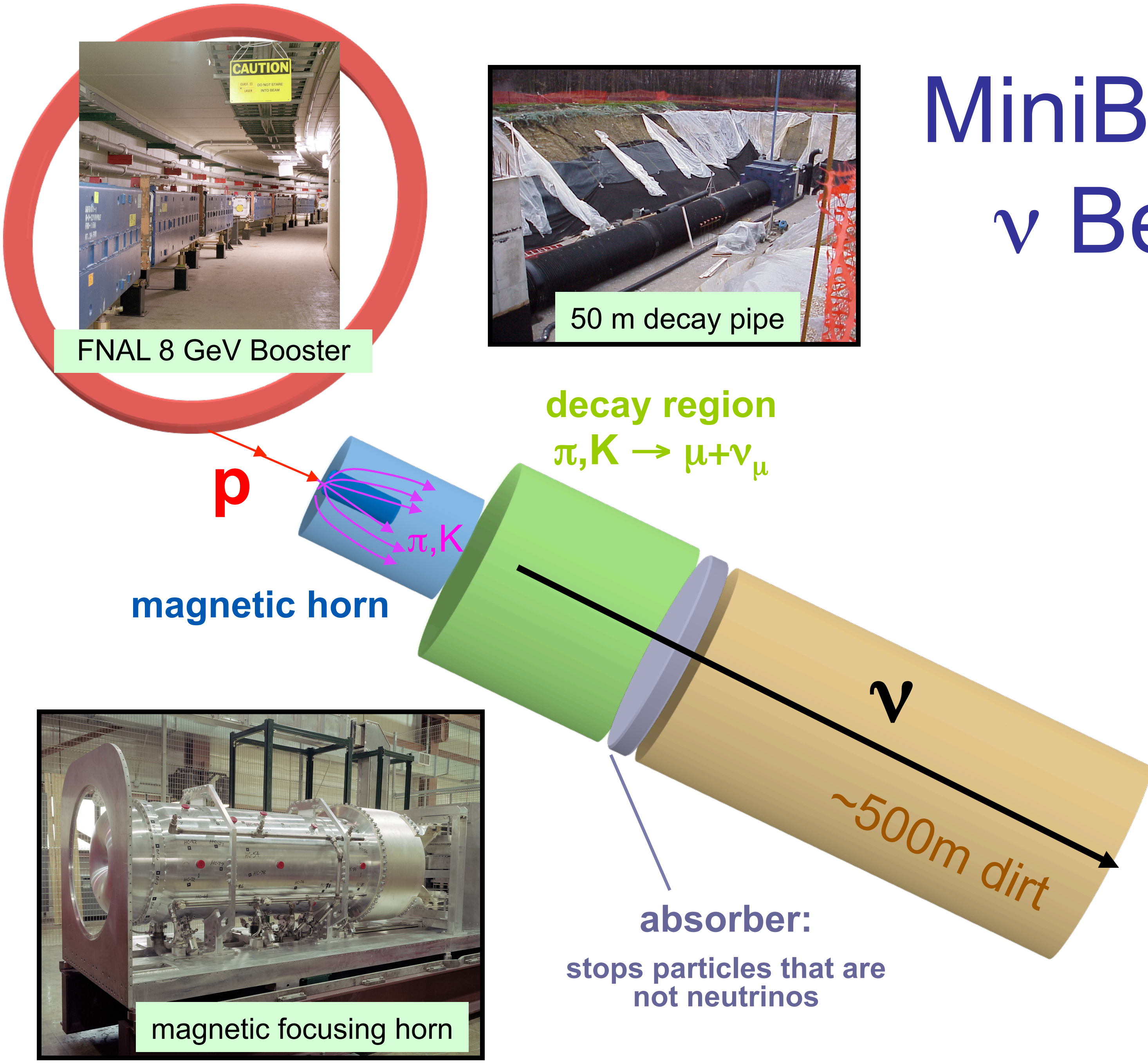
MiniBooNE
ν Beam



MiniBooNE
ν Beam



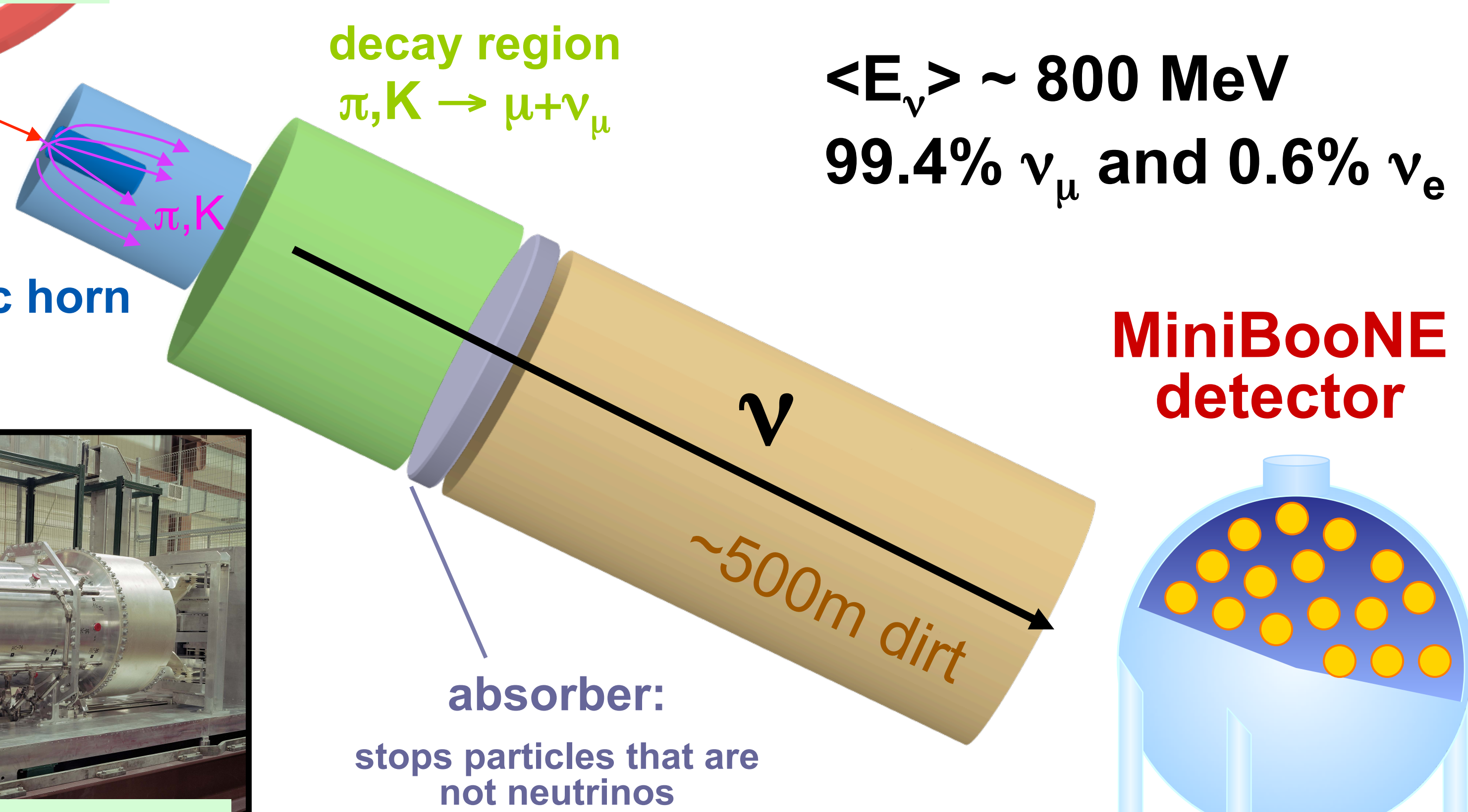
MiniBooNE
ν Beam

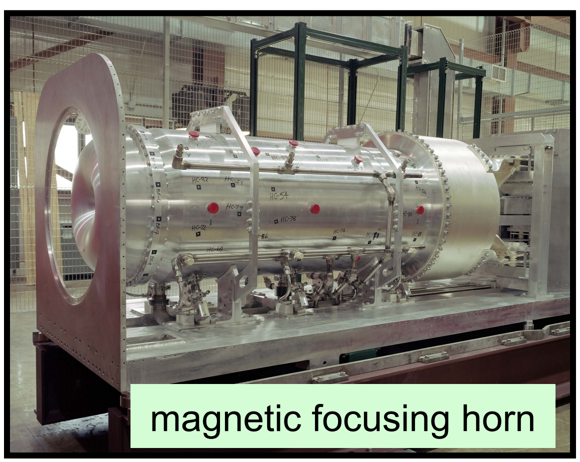


MiniBooNE
ν Beam

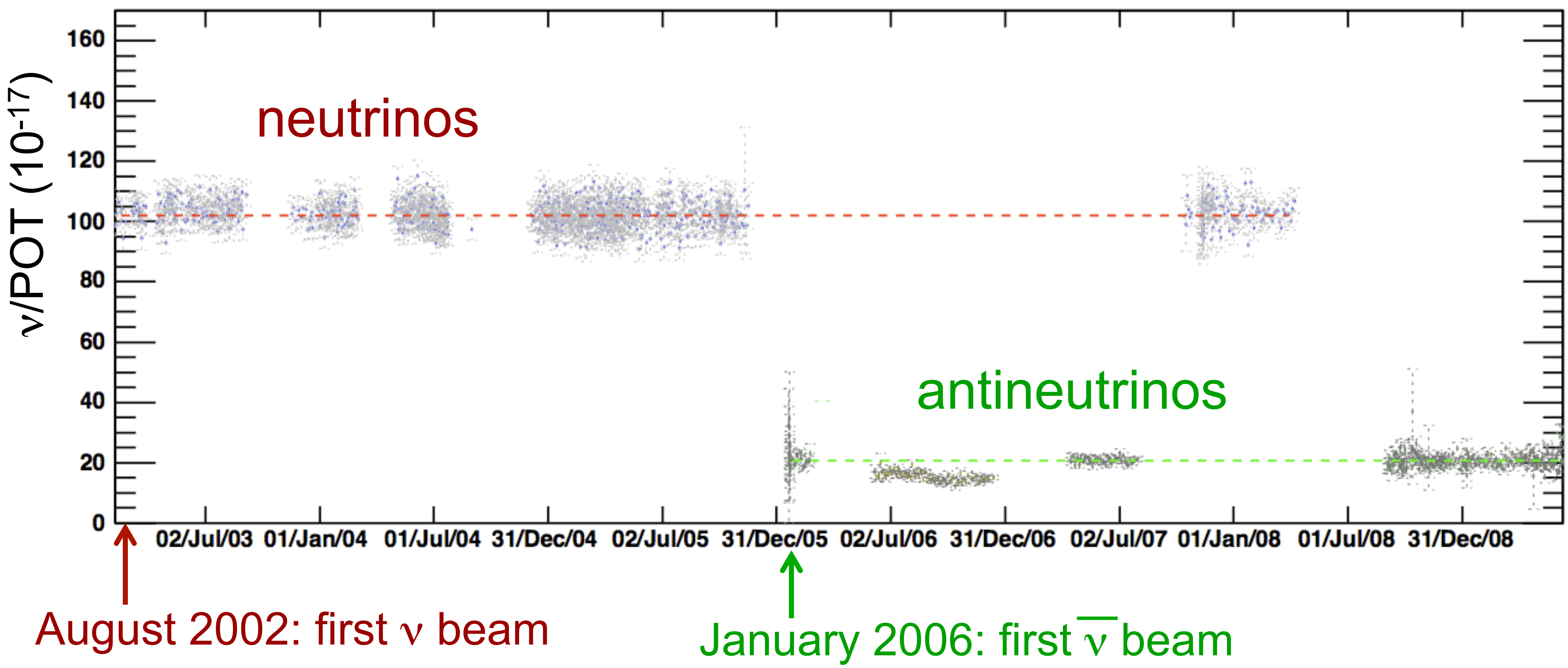
$\langle E_\nu \rangle$ ~ 800 MeV

99.4% ν_μ and 0.6% ν_e



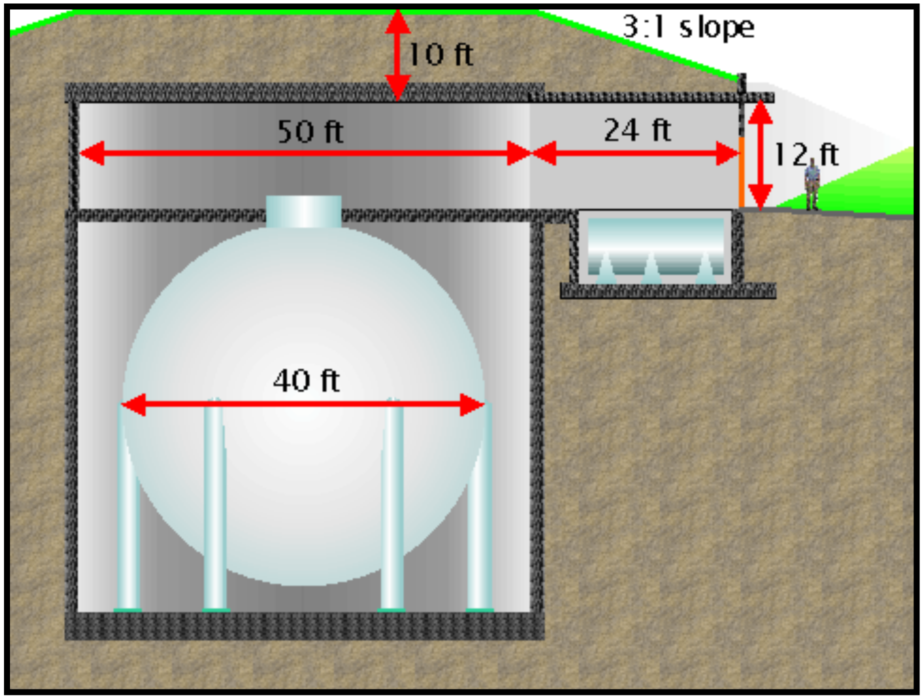


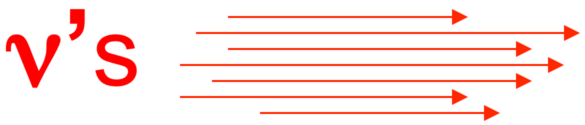
Neutrino Collection



- for every quadrillion protons delivered, get 1ν that interacts
- have recorded a **total of ~1,00,000 neutrino interactions!**
- the most recorded at these energies (E_ν < 2 GeV) … ever

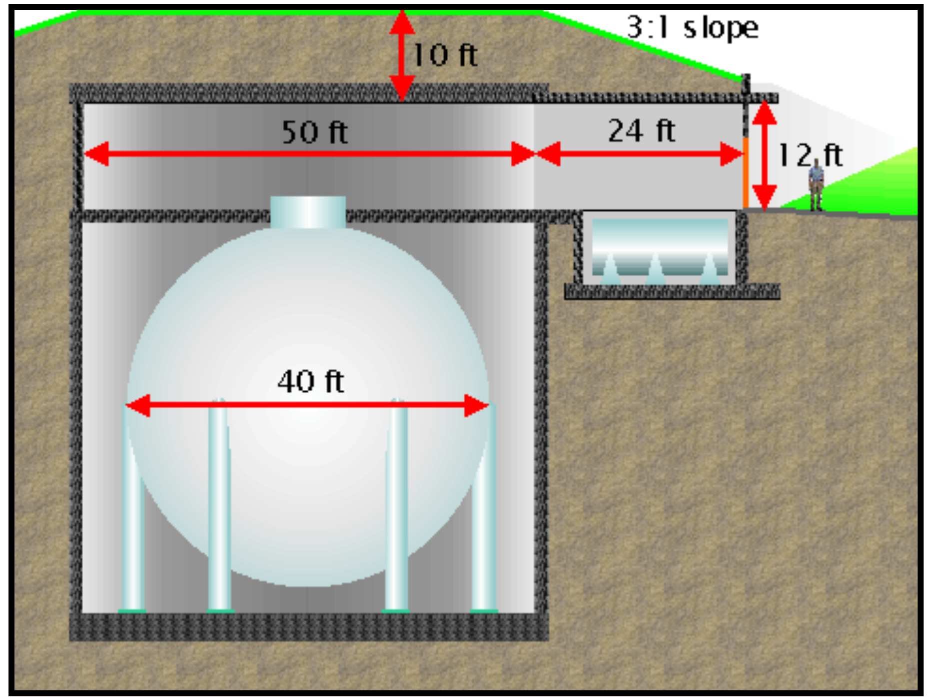
MiniBooNE Detector



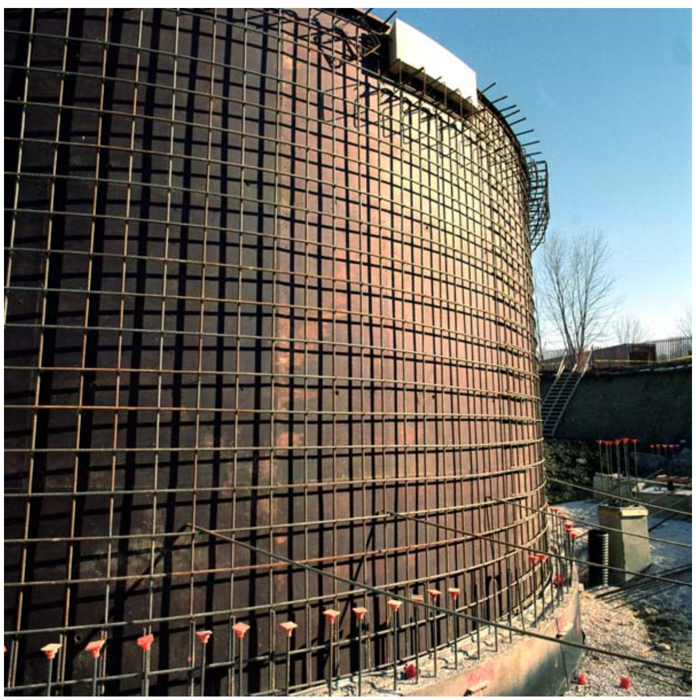


←detector built in 1999

MiniBooNE Detector



ν's



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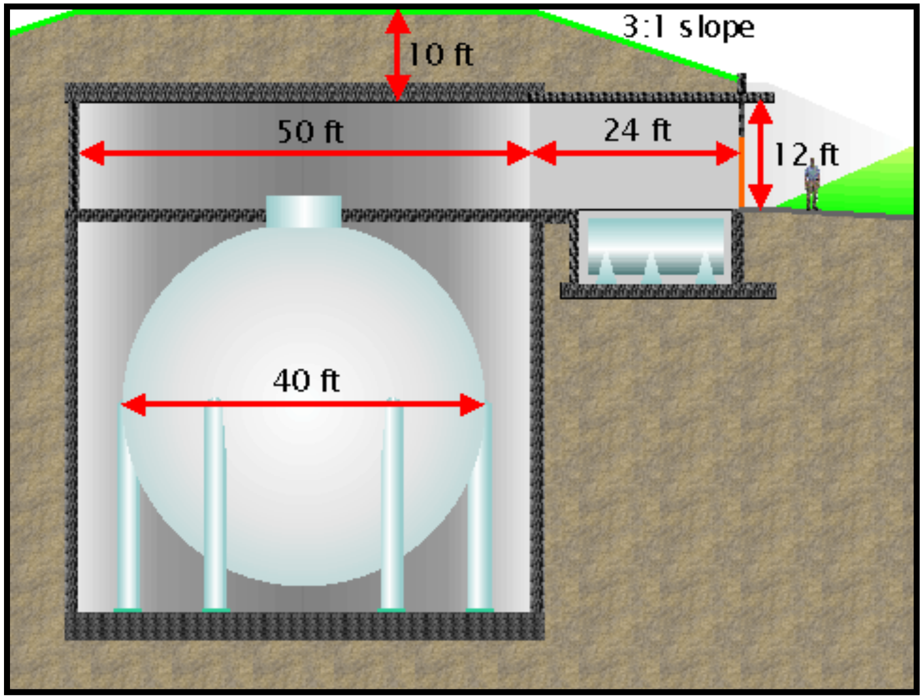
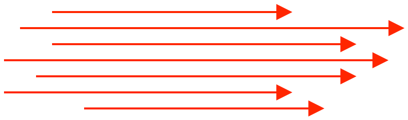
MiniBooNE Detector



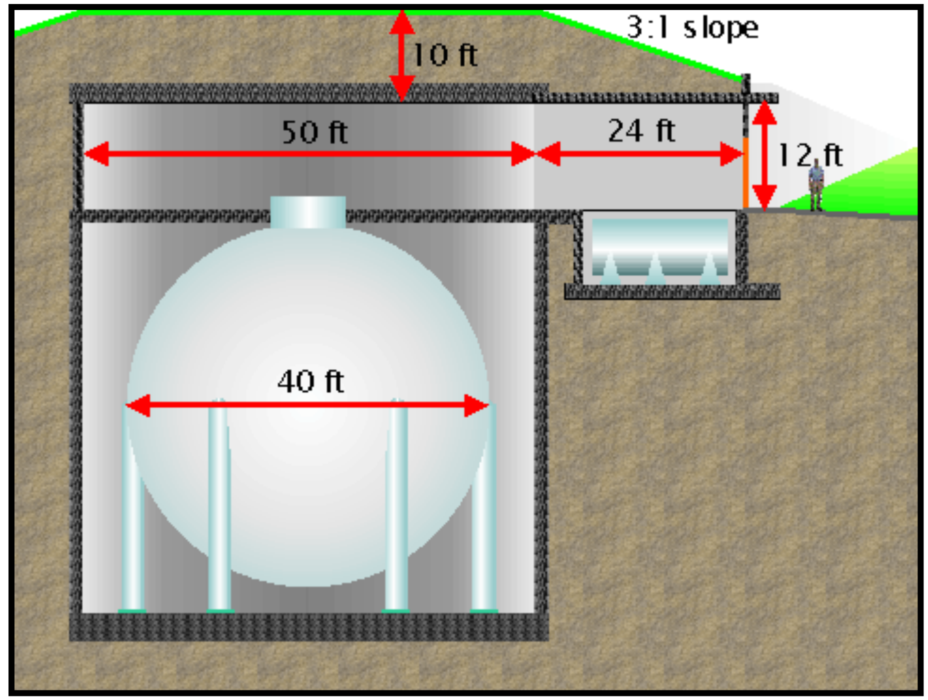
ν's



←detector built in 1999

MiniBooNE Detector

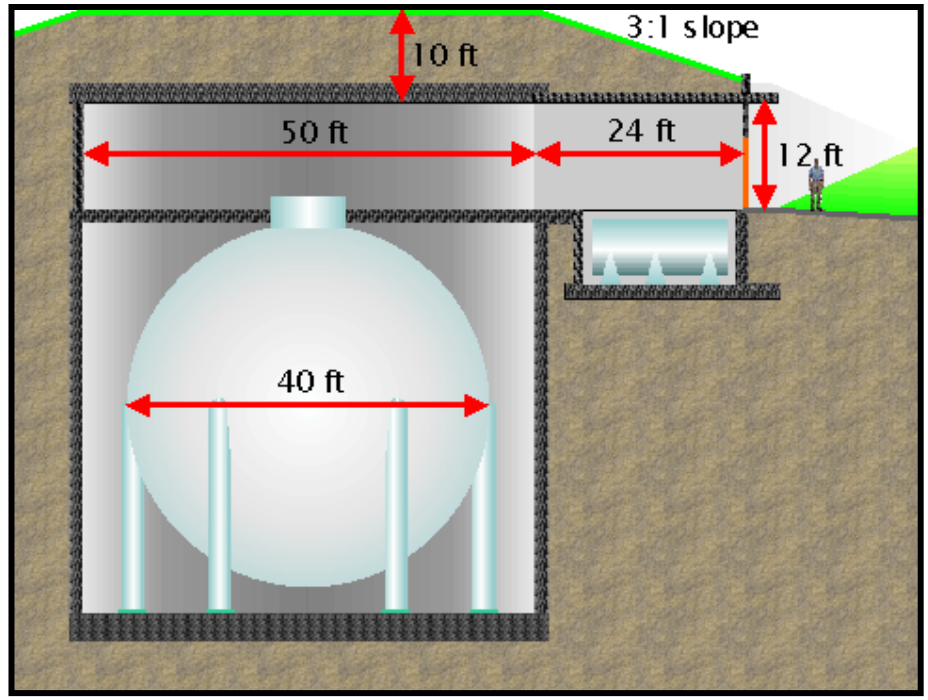
ν's



←detector built in 1999

MiniBooNE Detector

ν's



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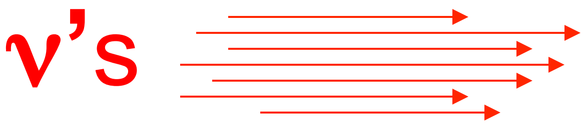
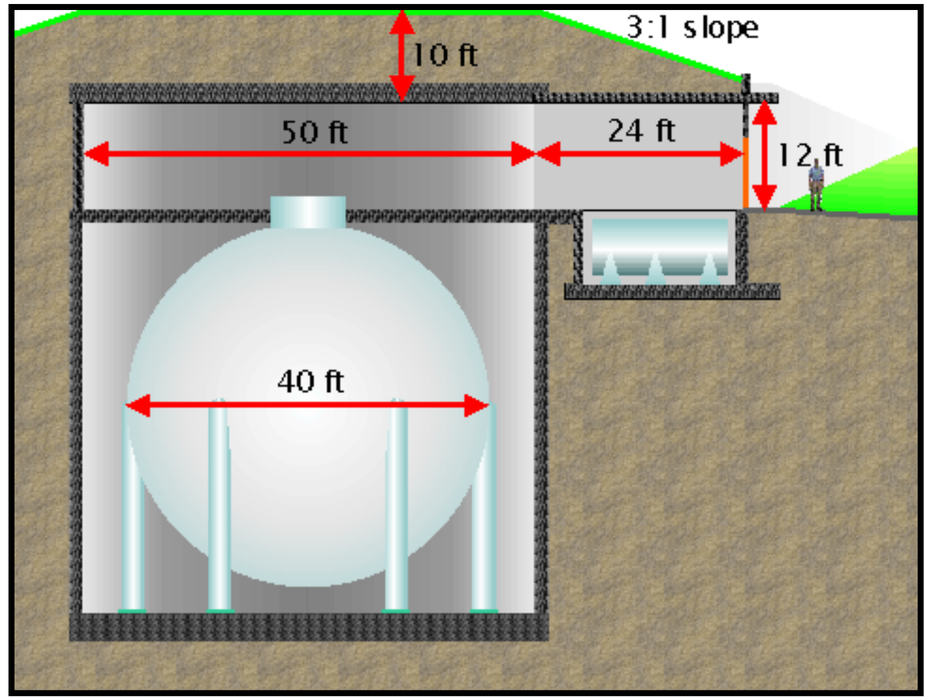
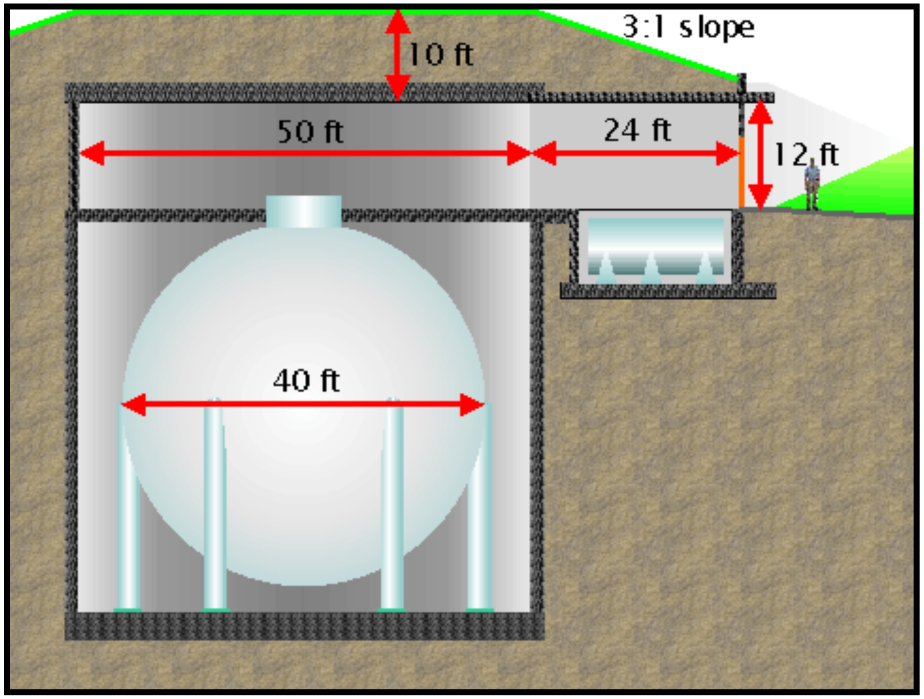
MiniBooNE Detector



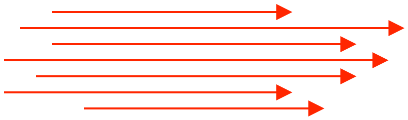


←detector built in 1999

MiniBooNE Detector



ν's



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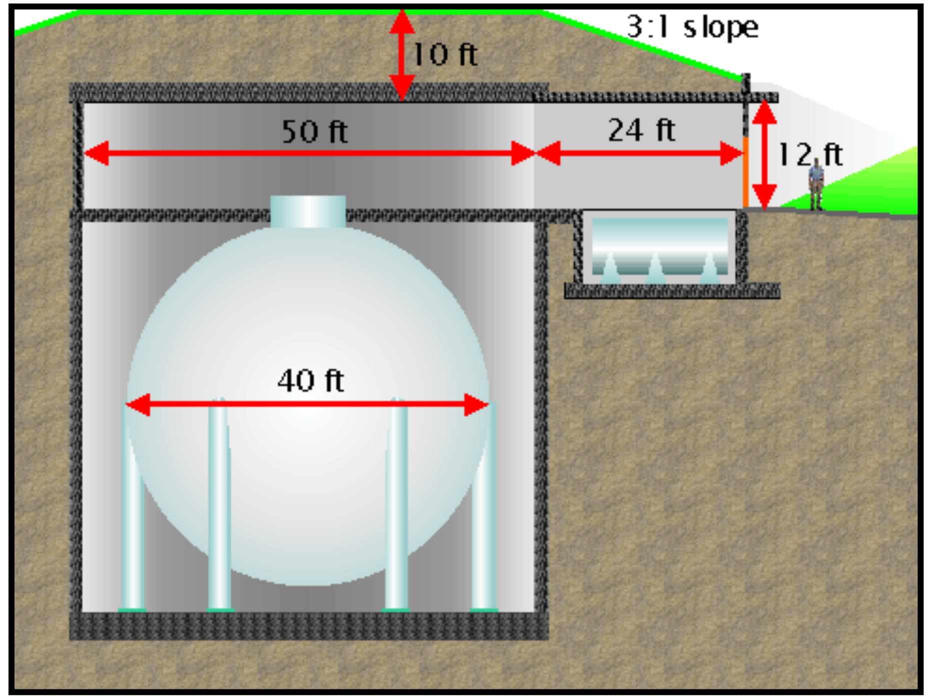
MiniBooNE Detector

ν's



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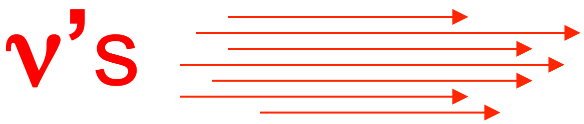
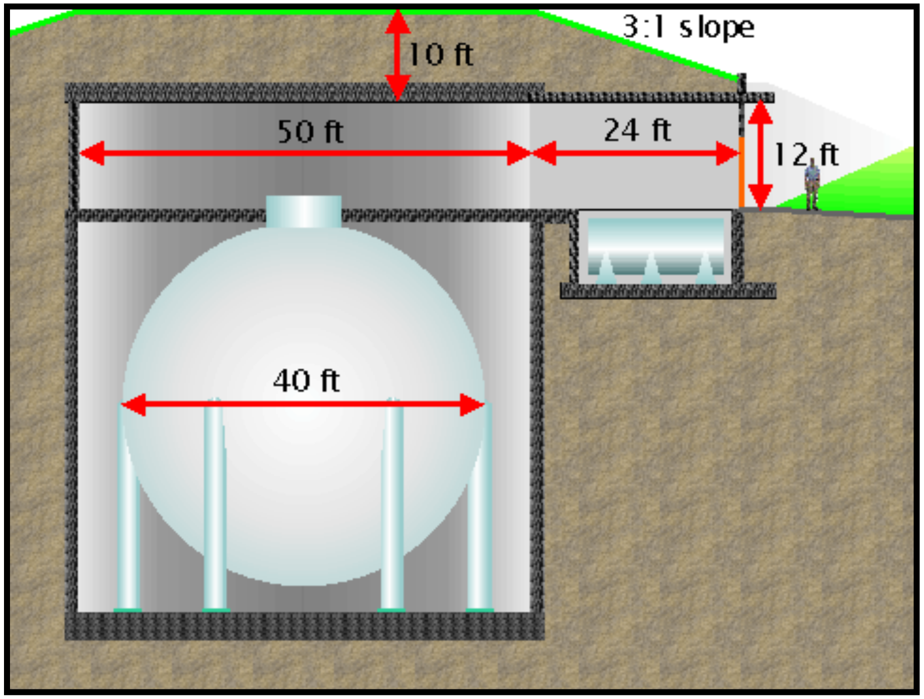
MiniBooNE Detector

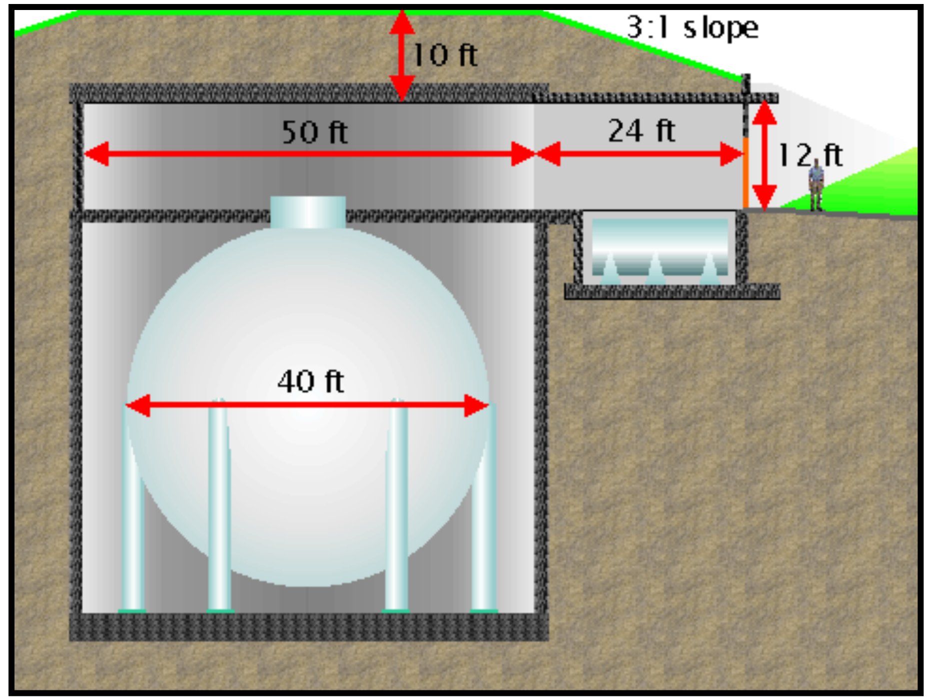




←detector built in 1999

MiniBooNE Detector

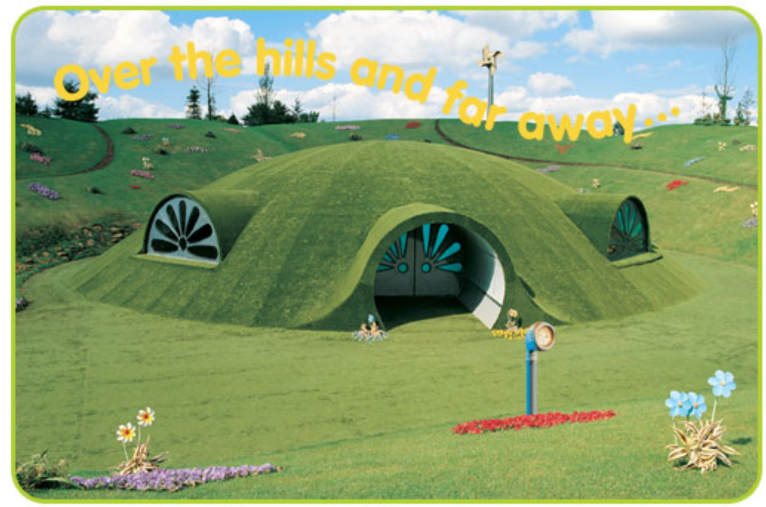
ν's



J. Raaf (Boston), E. Hawker (IMSA), C. Green (FNAL)

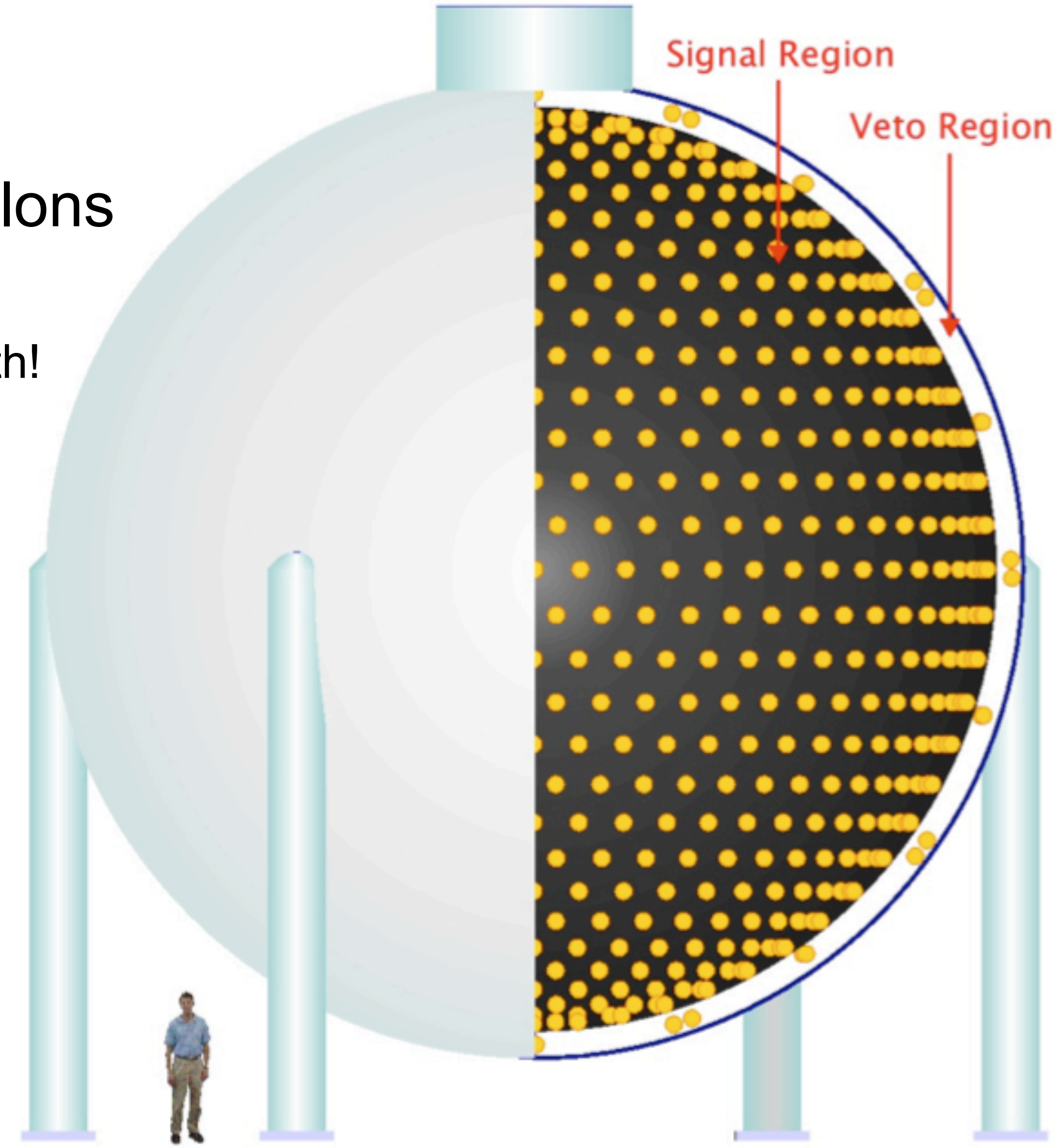
←detector built in 1999

Aerial View



Tank

- tank contains 250,000 gallons of **mineral oil** (ν target)
  - 800 ton! 44 tanker trucks worth!



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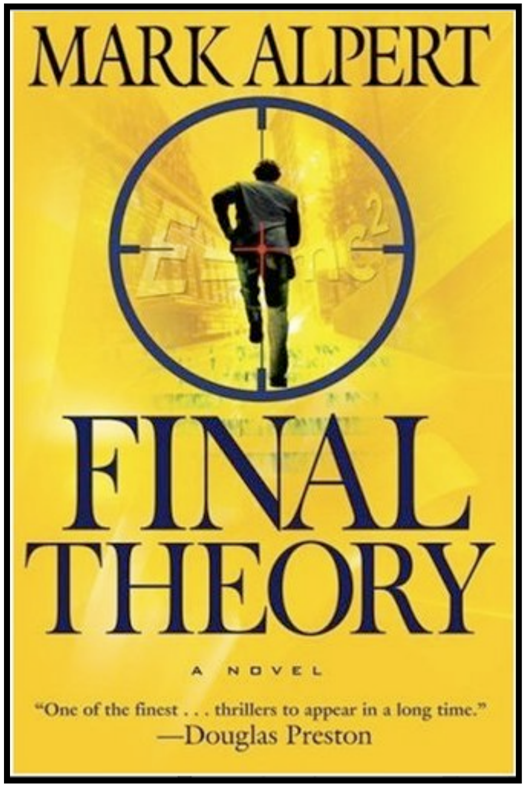
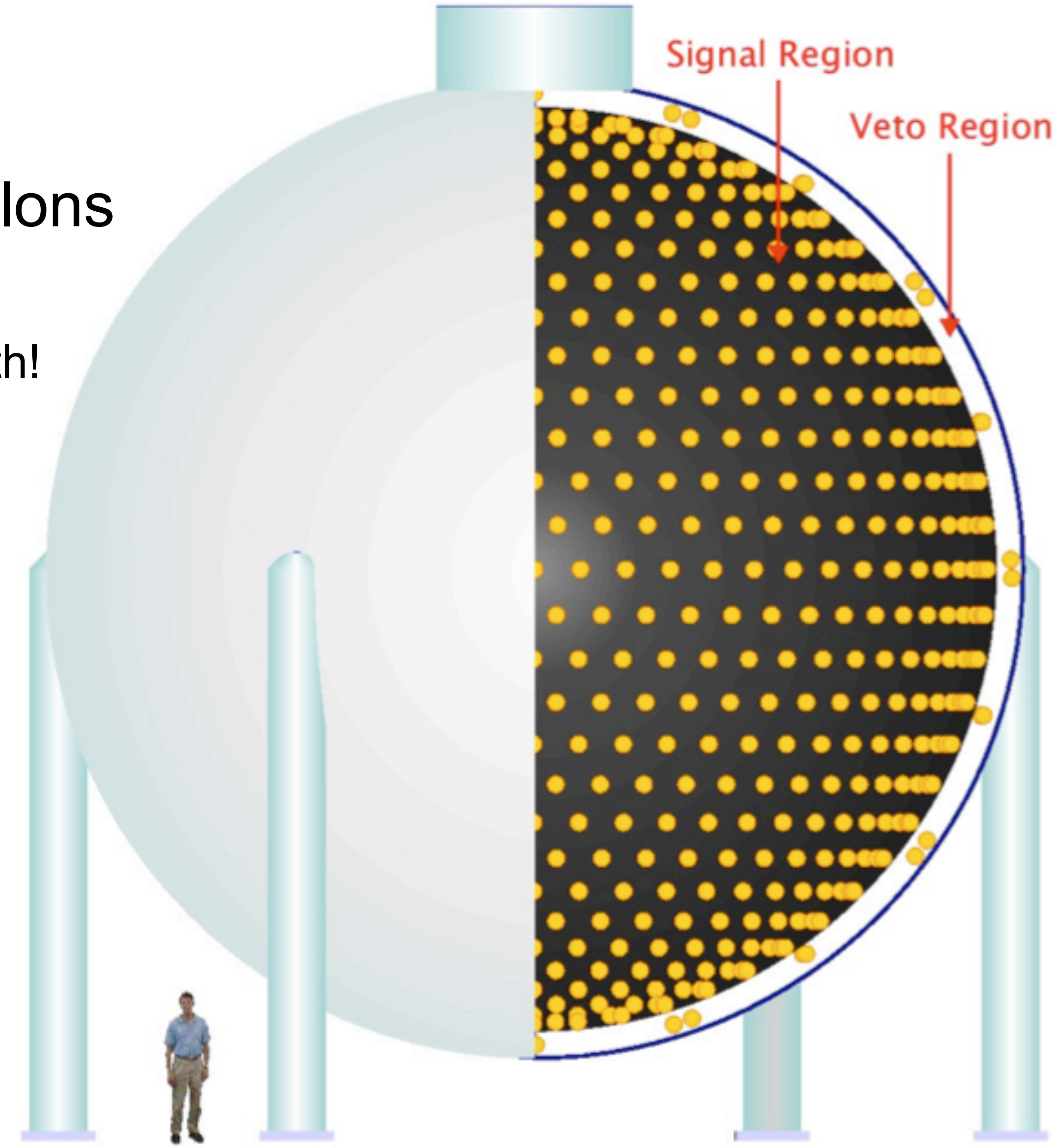
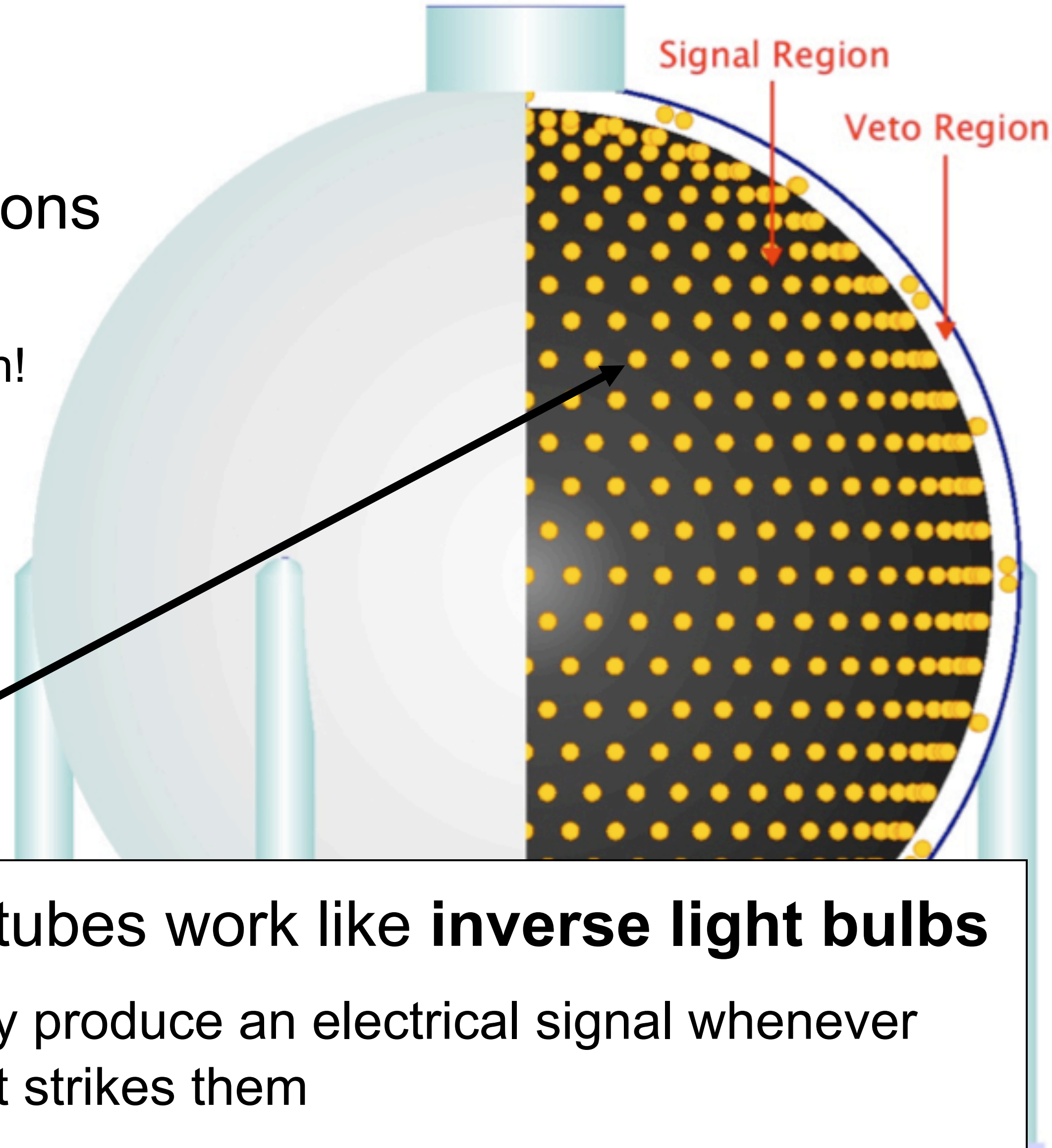




Tank

- tank contains 250,000 gallons of **mineral oil** (ν target)
  - 800 ton! 44 tanker trucks worth!
- products of ν ints → light (Cerenkov and scintillation)
- 1520 **PHOTOTUBES** ("eyes" of the detector)



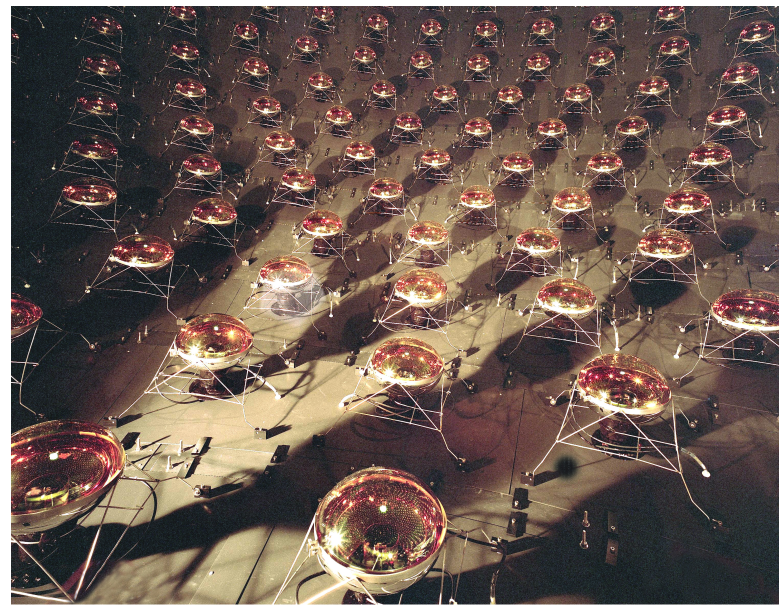
Phototubes work like **inverse light bulbs**

- they produce an electrical signal whenever light strikes them
- common technique: light as evidence for ν!

Inside

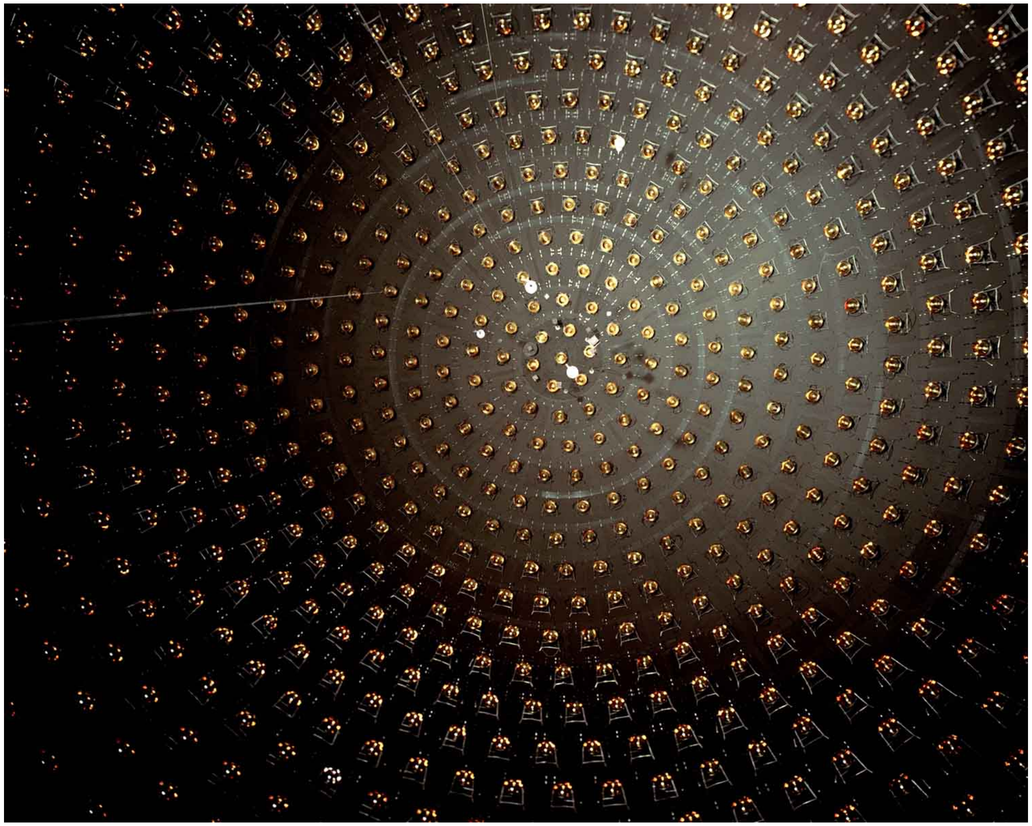
P. Meyers (Princeton)

these phototubes are completely submerged in the mineral oil inside the sealed tank



• tell us charge and time

Inside

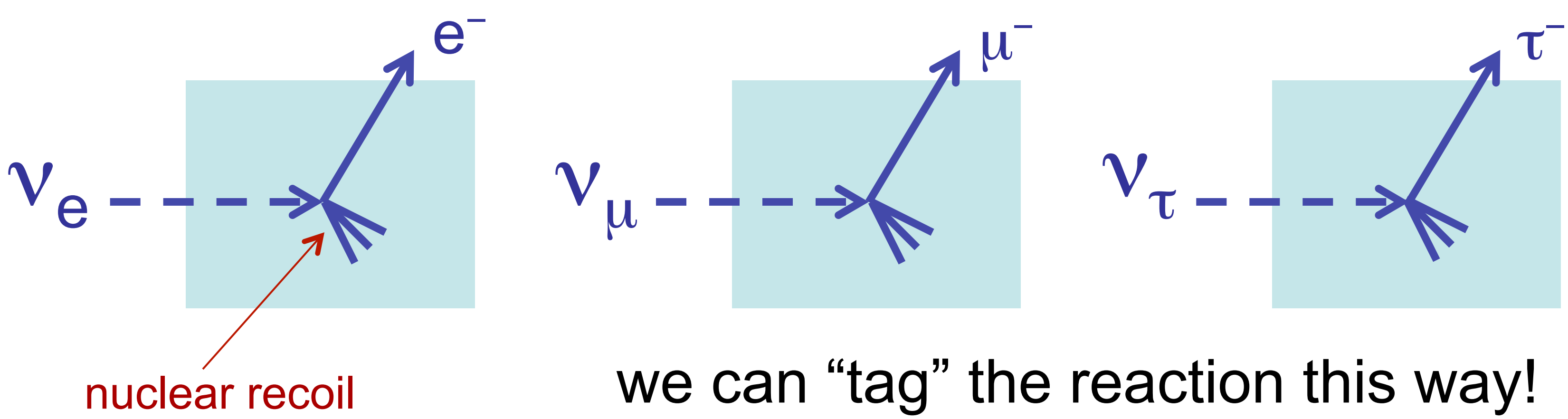


R. Tayloe (Indiana)

- we have a beam of **lots of ν's** & a **massive detector**, but how are we going to know ν's have interacted inside?

Seeing the Invisible Neutrino

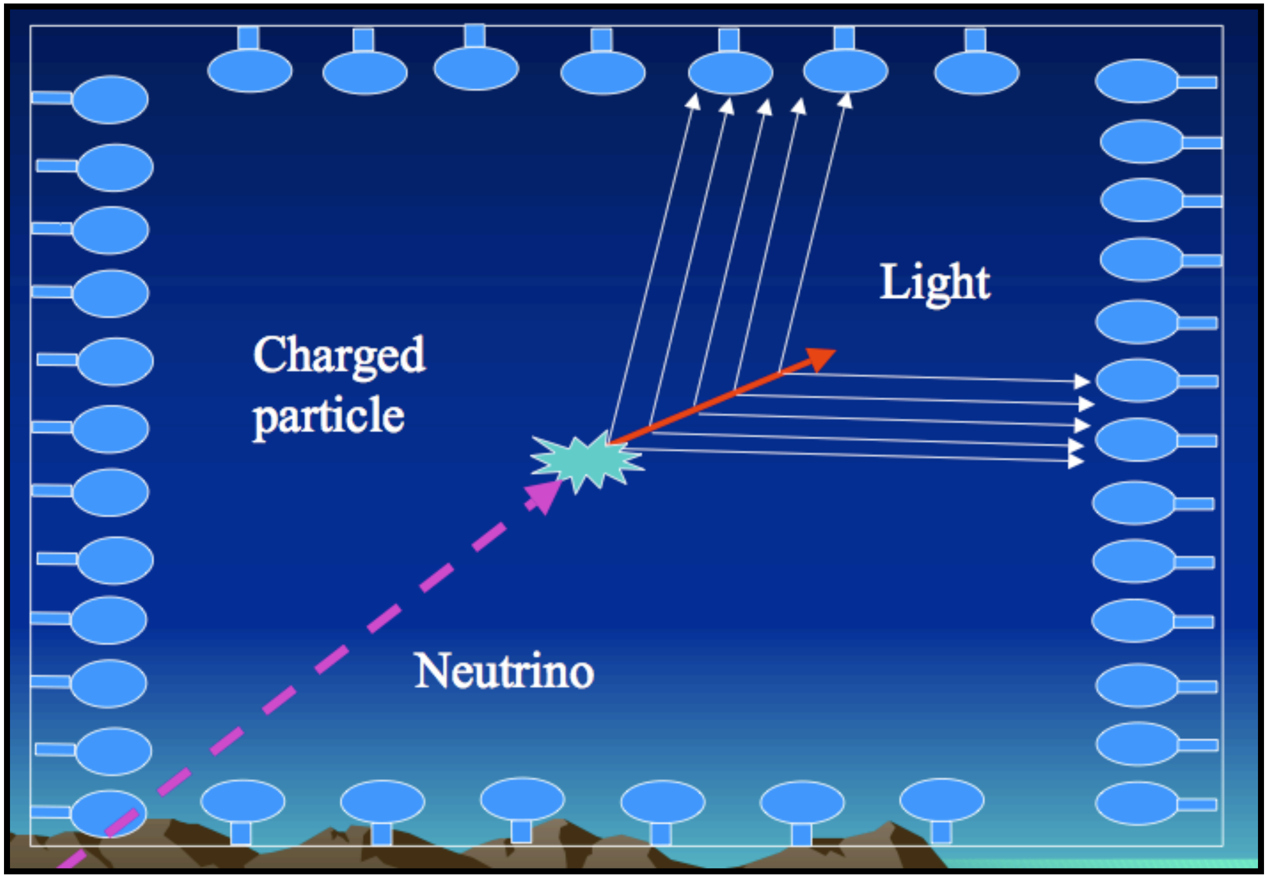
- we can only **"see"** particles that are electrically **charged**
- can detect a ν ONLY if it hits something & knocks out or produces a **charged particle**
- remember: a ν can **interact** by scattering off a target and changing into its own charged partner (CC)



we can "tag" the reaction this way!

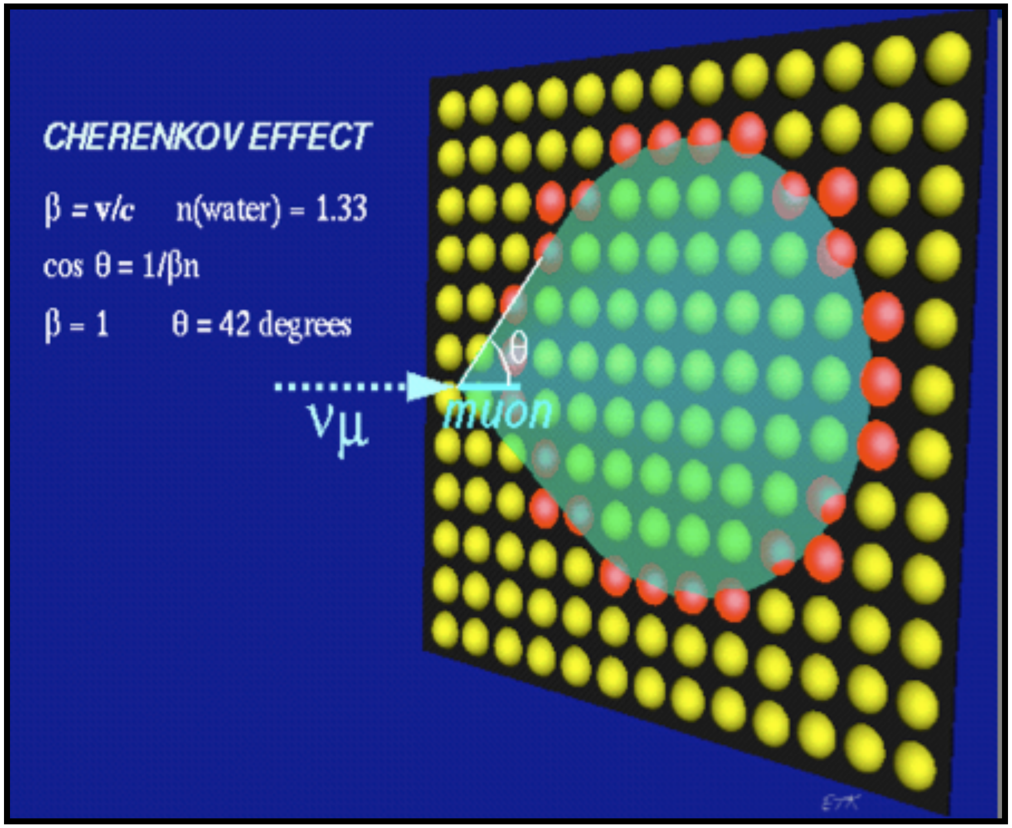
Seeing the Invisible Neutrino

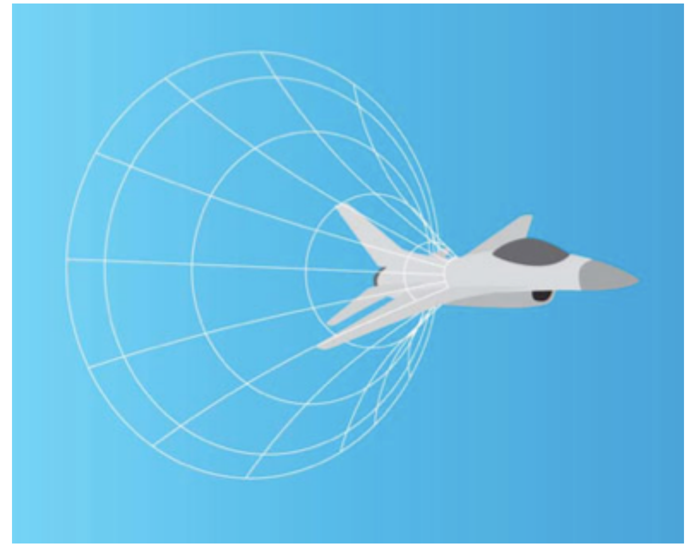
- we "see" μ and e through their production of light



- very simple set-up

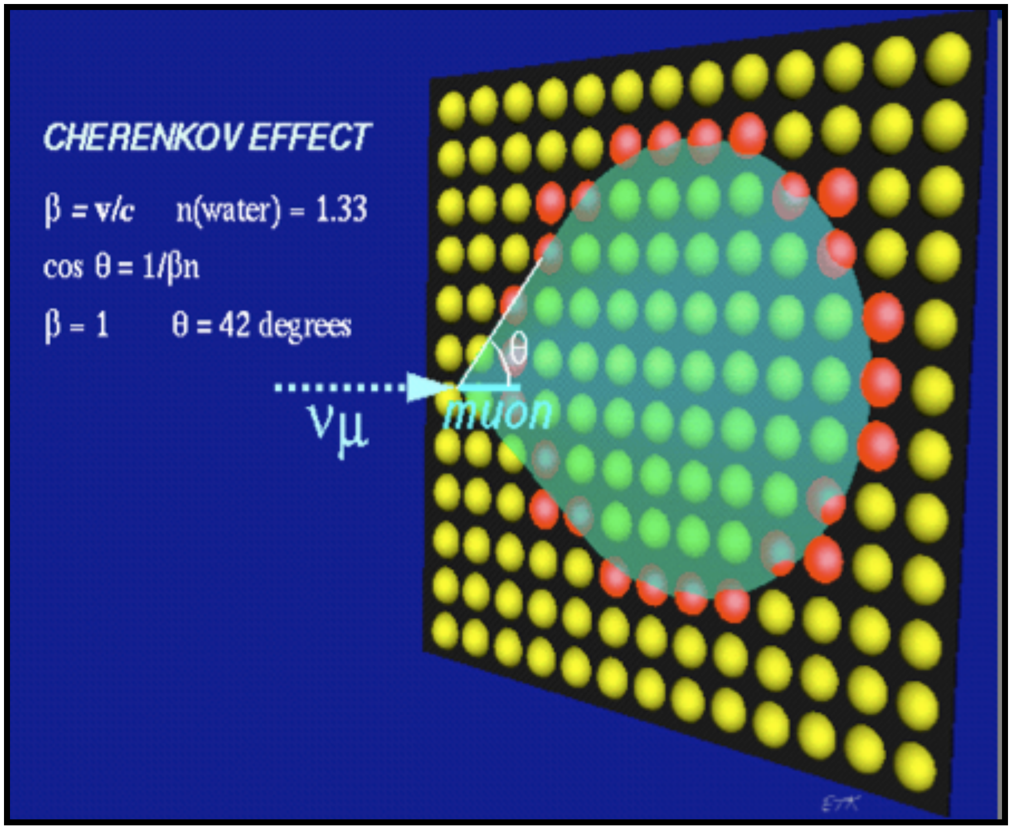
Cerenkov Light

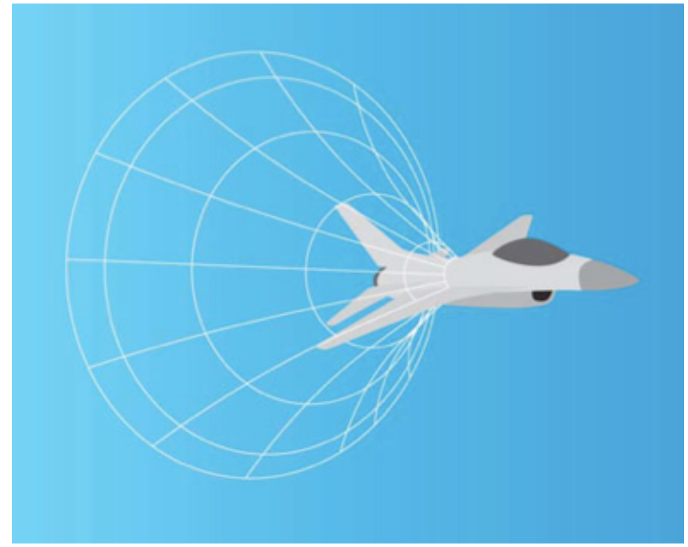


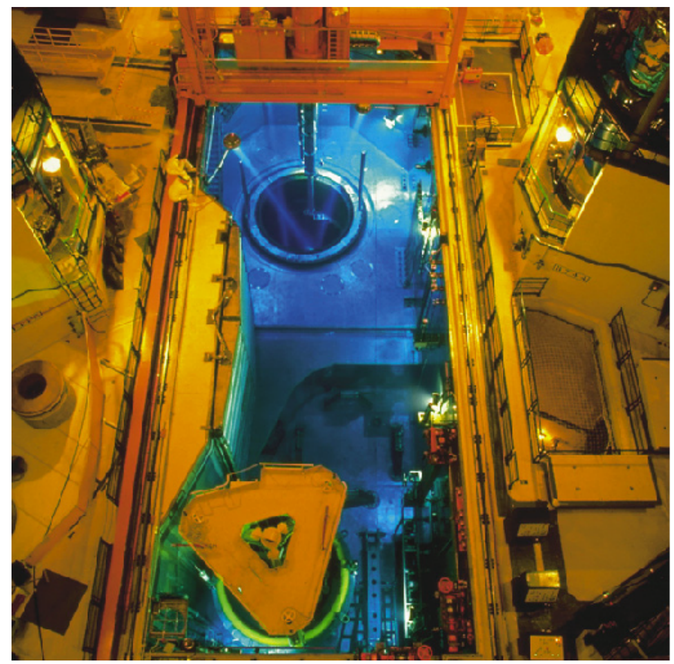


- charged particles traveling faster than speed of light in a liquid can create a “shock wave” of light (optical boom)

Cerenkov Light

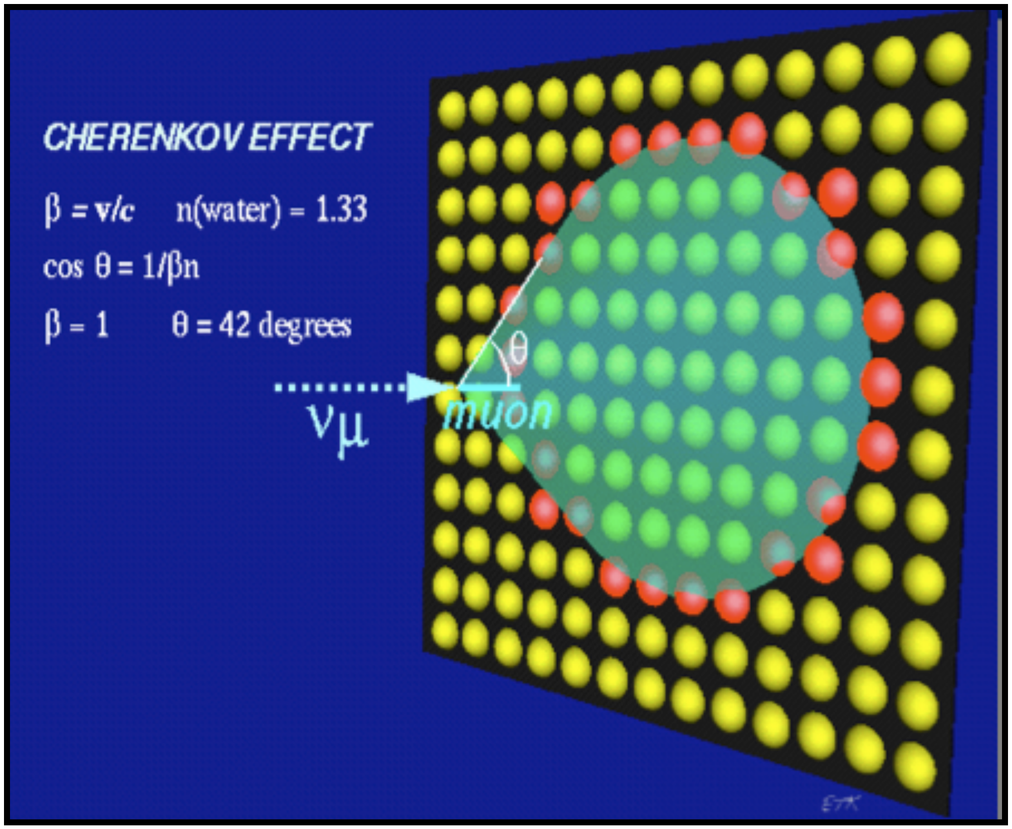


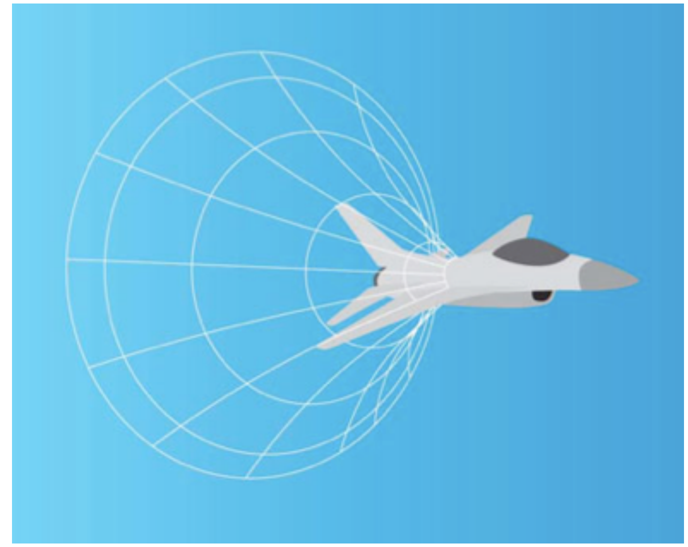




same phenomenon which causes reactor core to glow brilliant blue color

Cerenkov Light



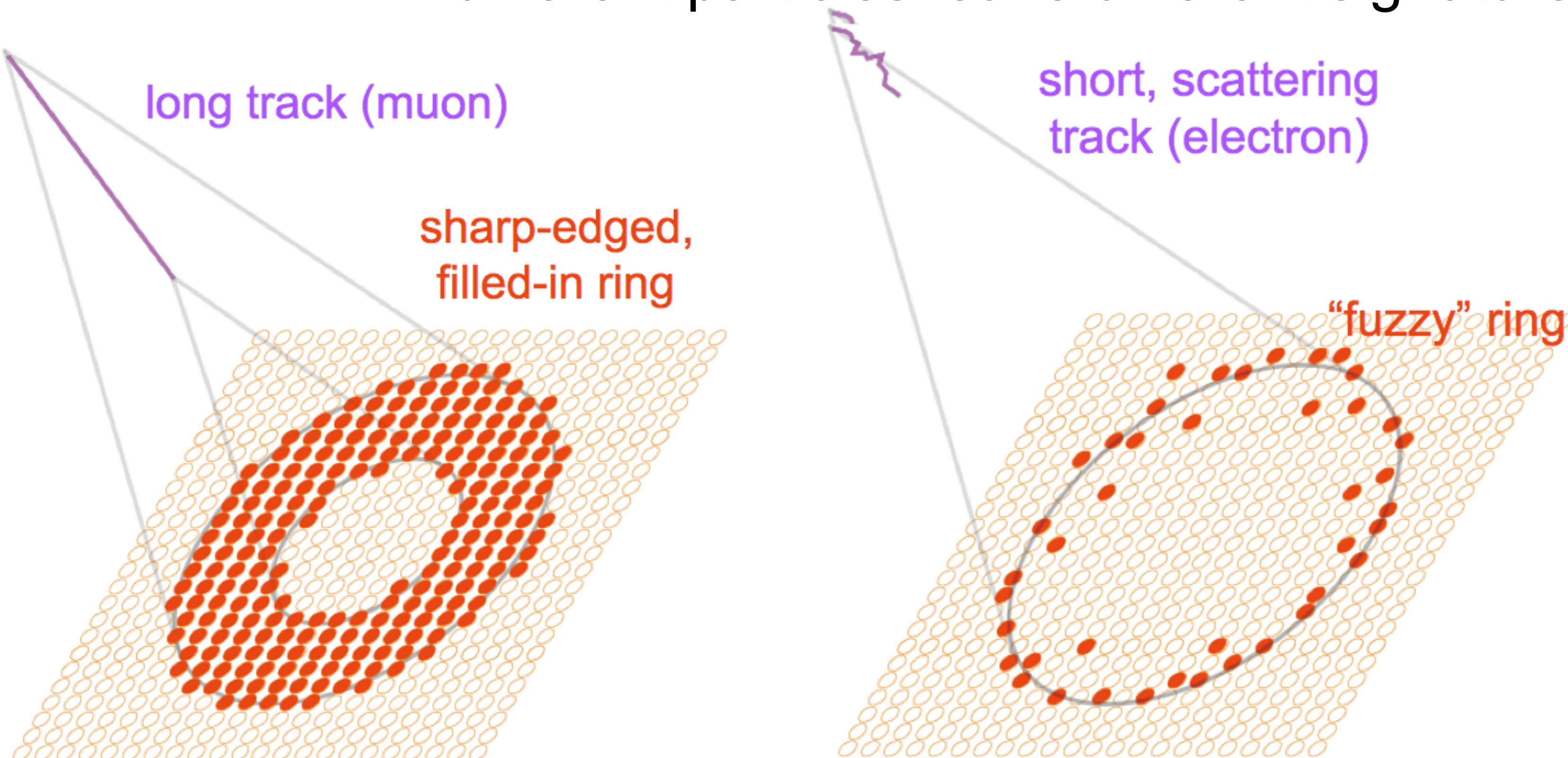


- light is very dim so need exquisitely sensitive light detectors (PMTs)

- Cerenkov light forms a **cone** that expands along particle's trajectory; when projected on detector wall, cone leaves characteristic **ring-like** pattern on the array of photomultiplier tubes (we rely on ring imaging)

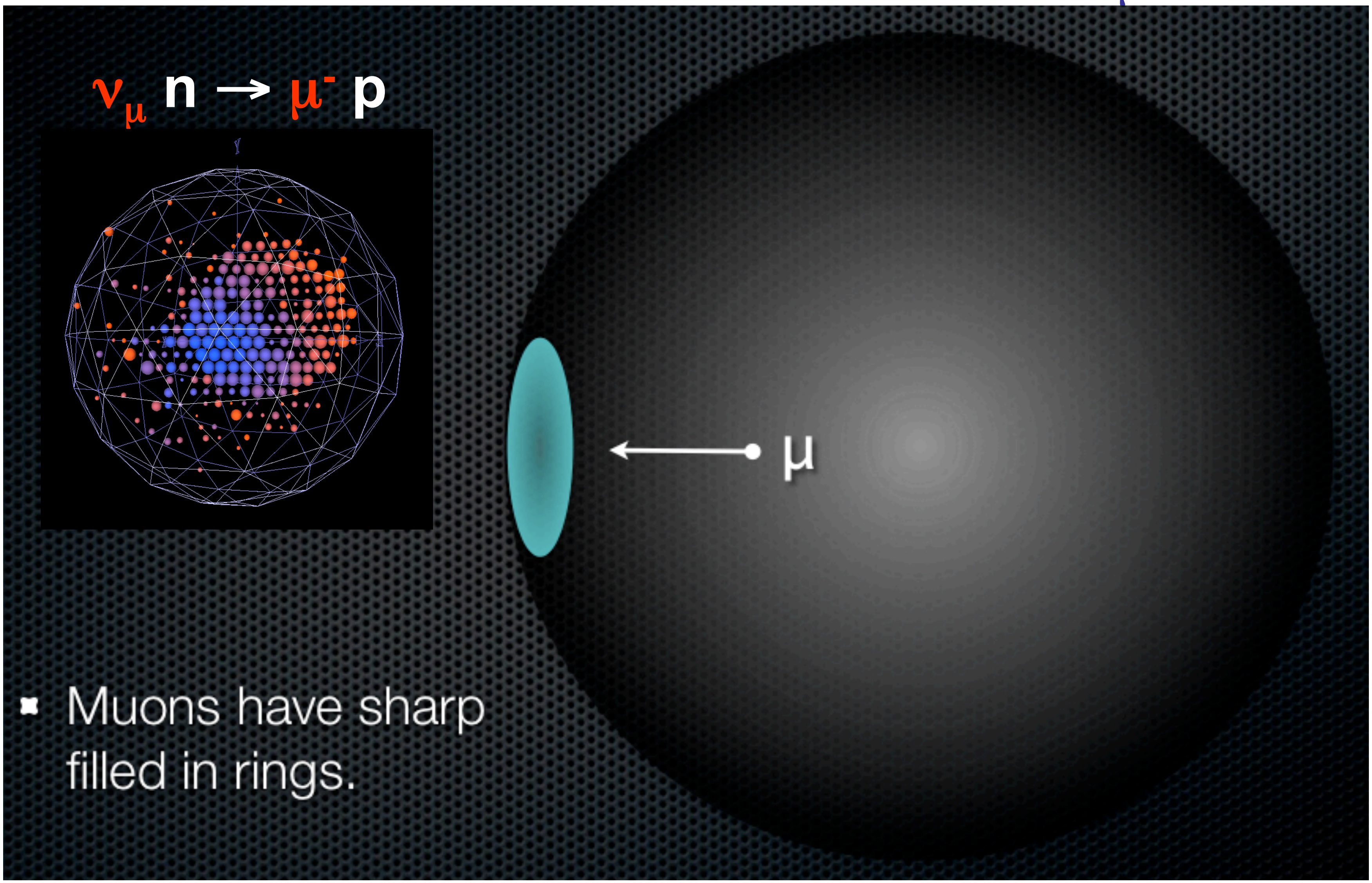
Modern Neutrino Hunting

different particles leave different signatures



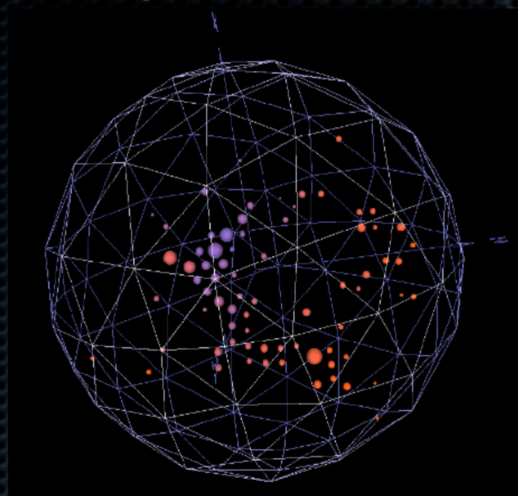
but what do these signatures look like in a real detector?

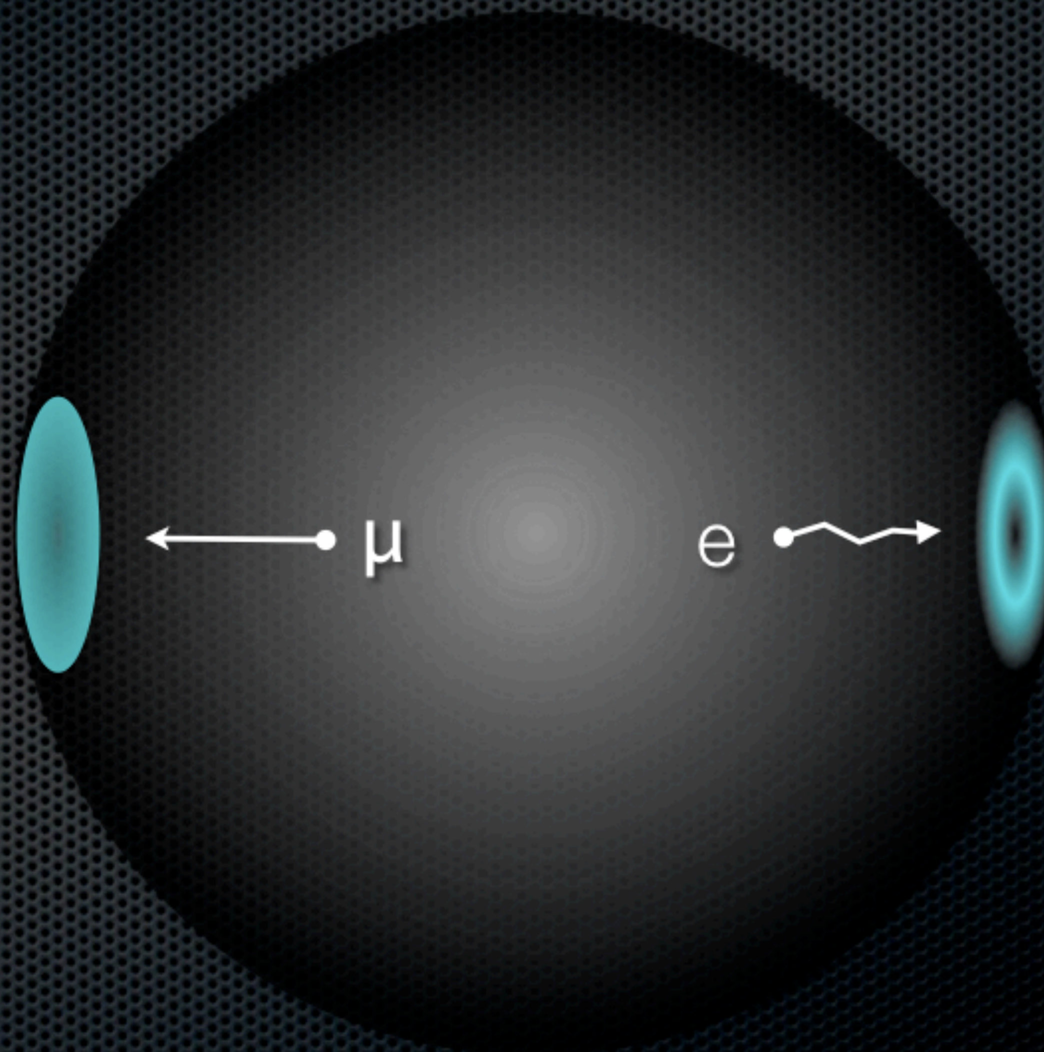
Muons Are a Sign of ν_μ



Electrons Are a Sign of ν_e

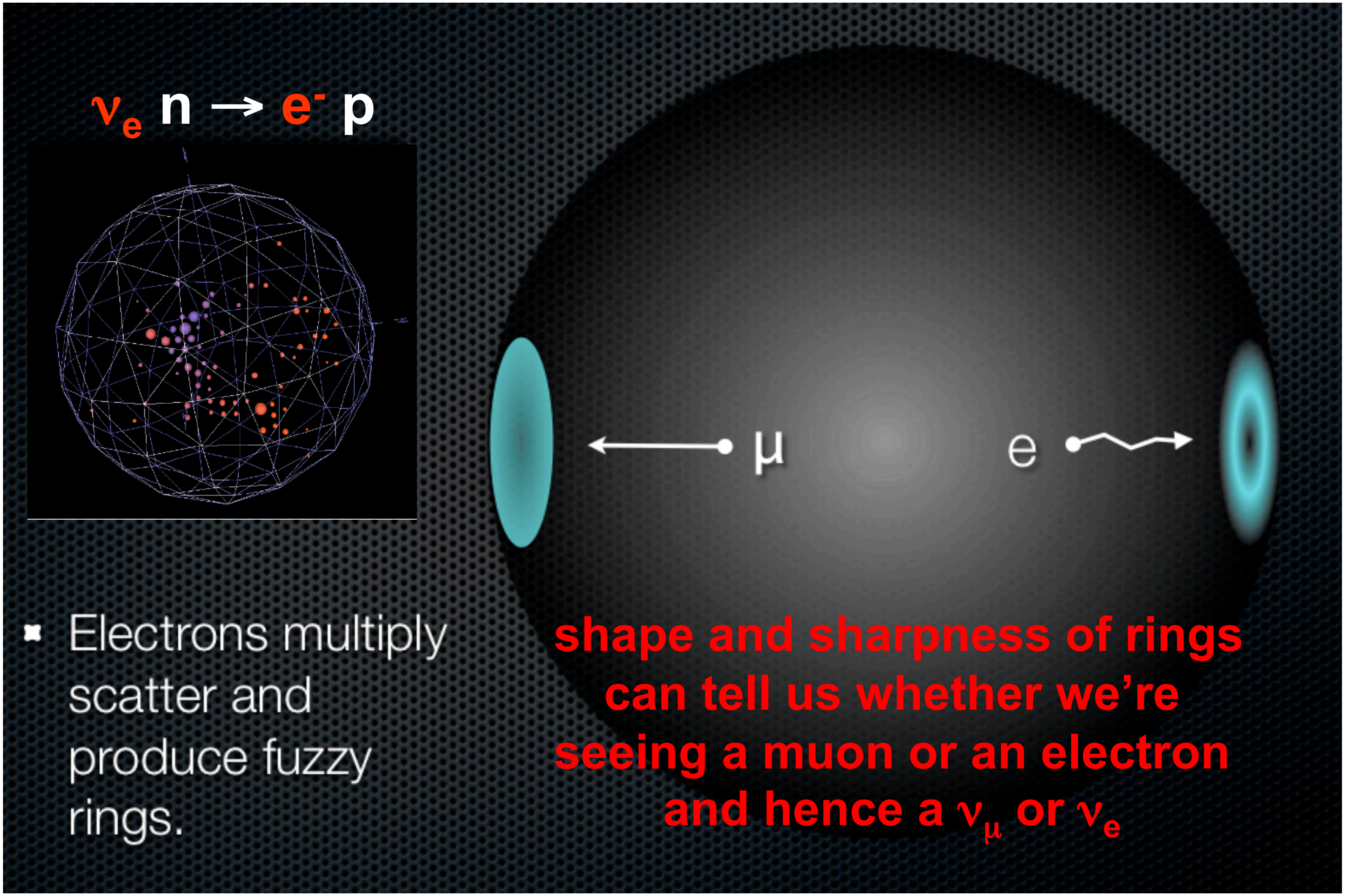
$\nu_e\, n \rightarrow e^-\, p$



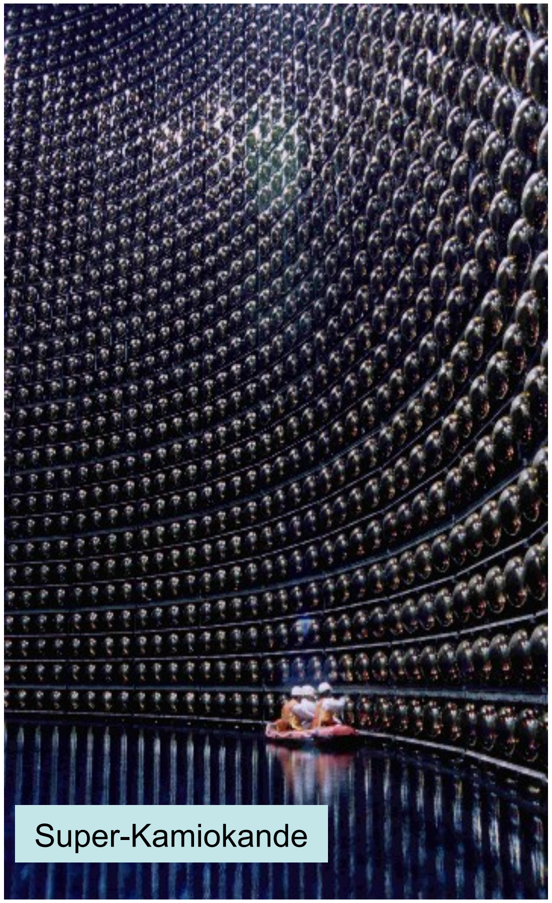


- Electrons multiply scatter and produce fuzzy rings.

Electrons Are a Sign of ν_e



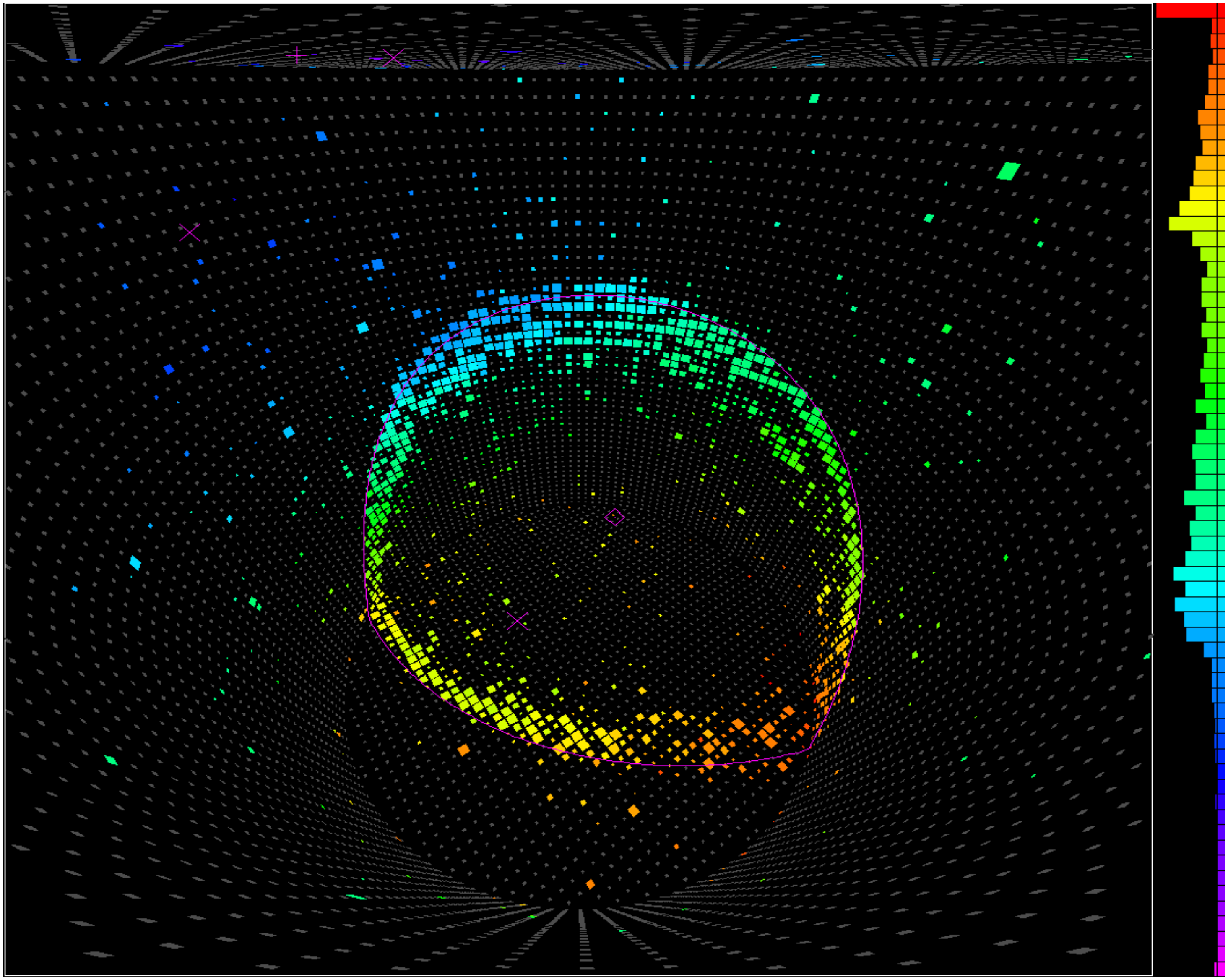
Super-K



• deep in Kamioka mine, Japan
• 50,000 tons ultra-pure water
• ~11,000 phototubes

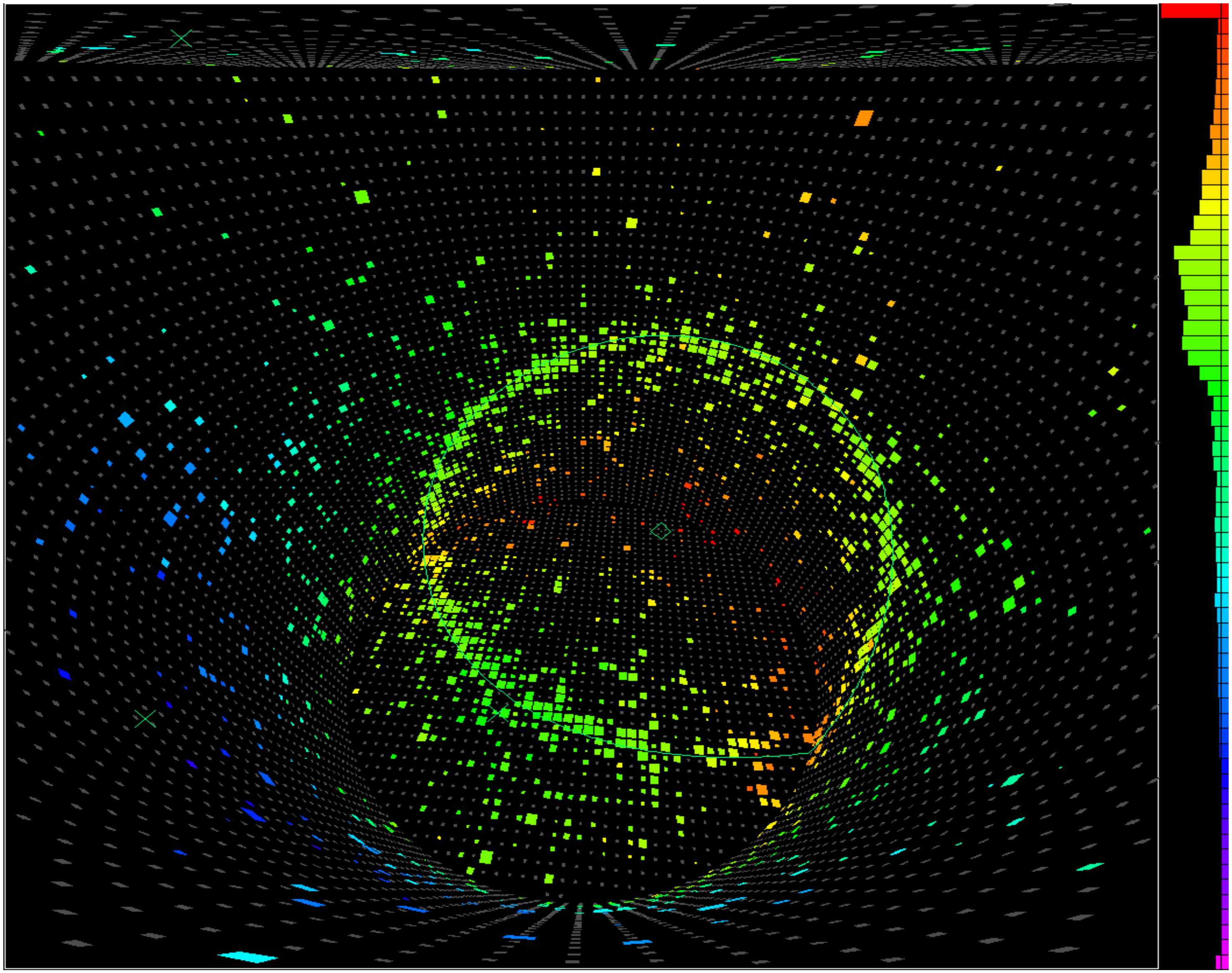
Super-K

muon
(sharp outer edge)

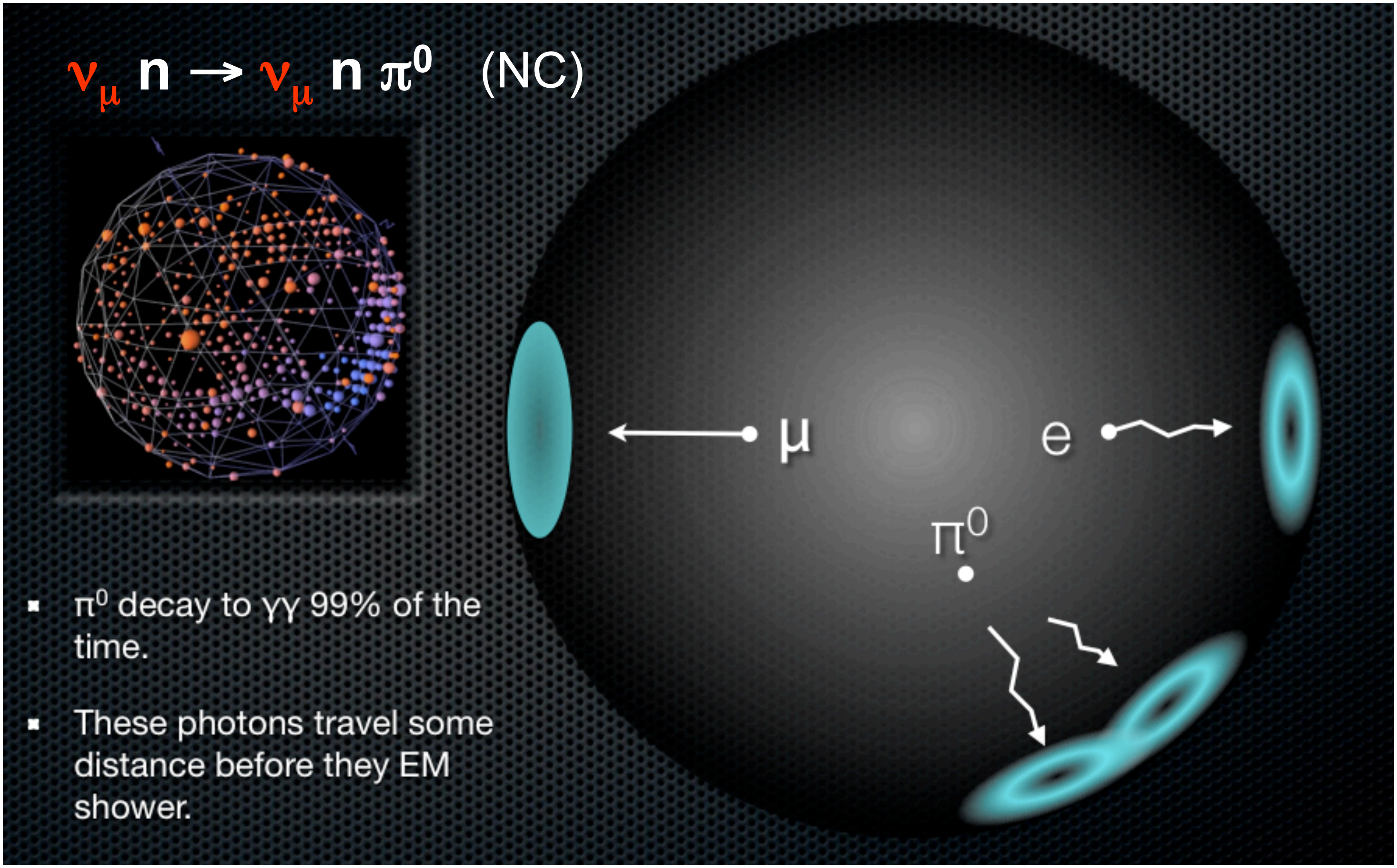


Super-K

electron
(fuzzy ring)



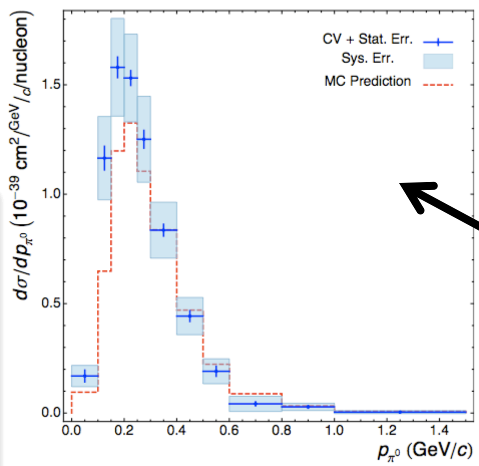
It's Not That Simple



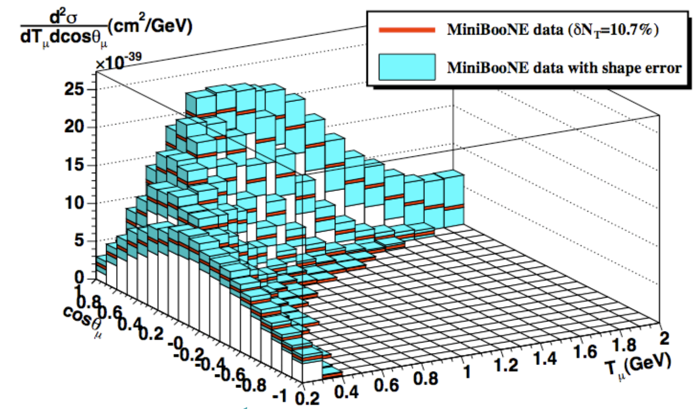
this is an important background!

Neutrinos in Oil

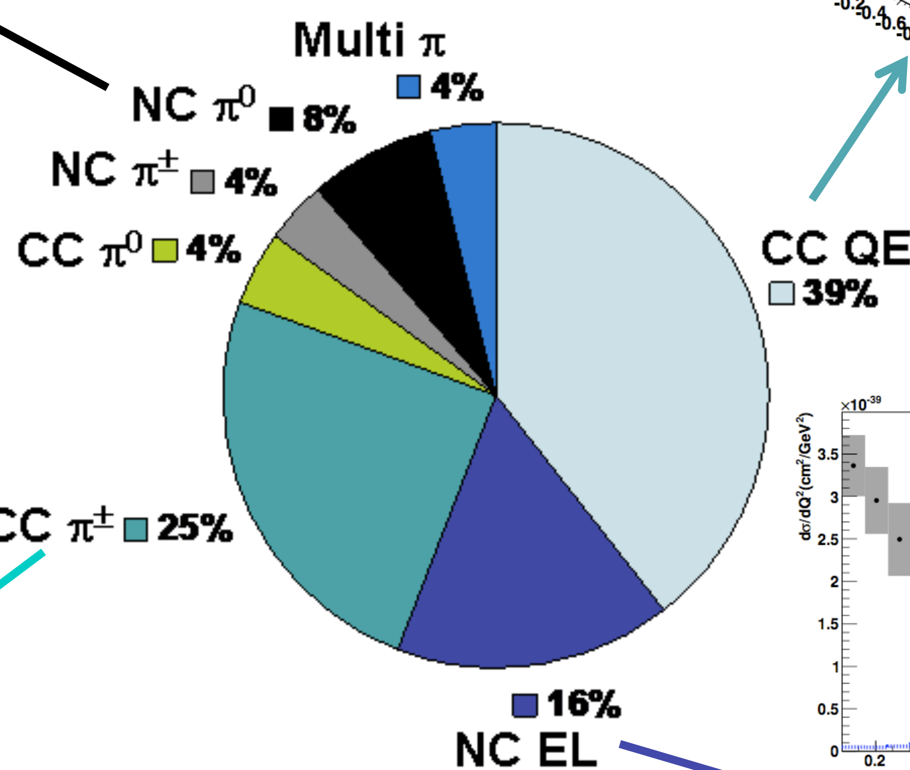
- ν's can do many things in mineral oil

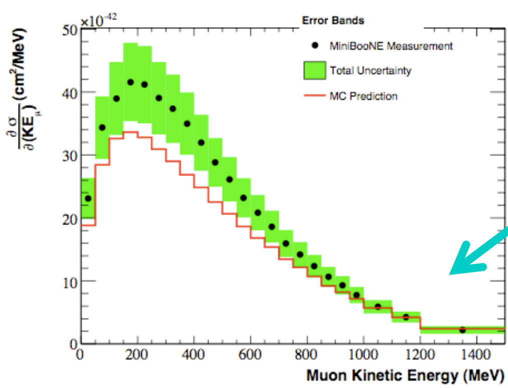


ν_μ N → ν_μ N π^0

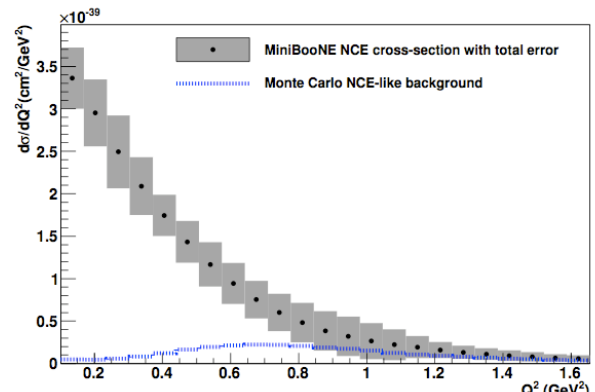


ν_μ n → μ^- p





ν_μ N → μ^- N π^+



ν_μ N → ν_μ N

Neutrinos in Oil

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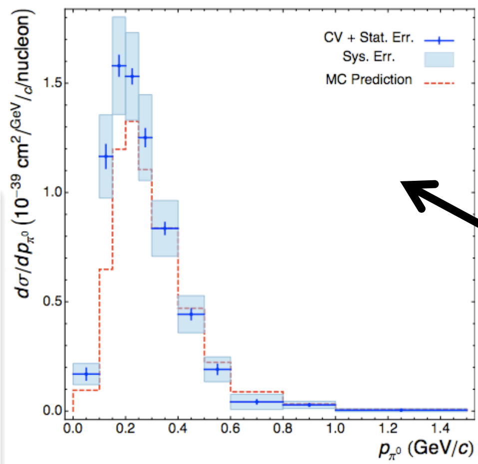
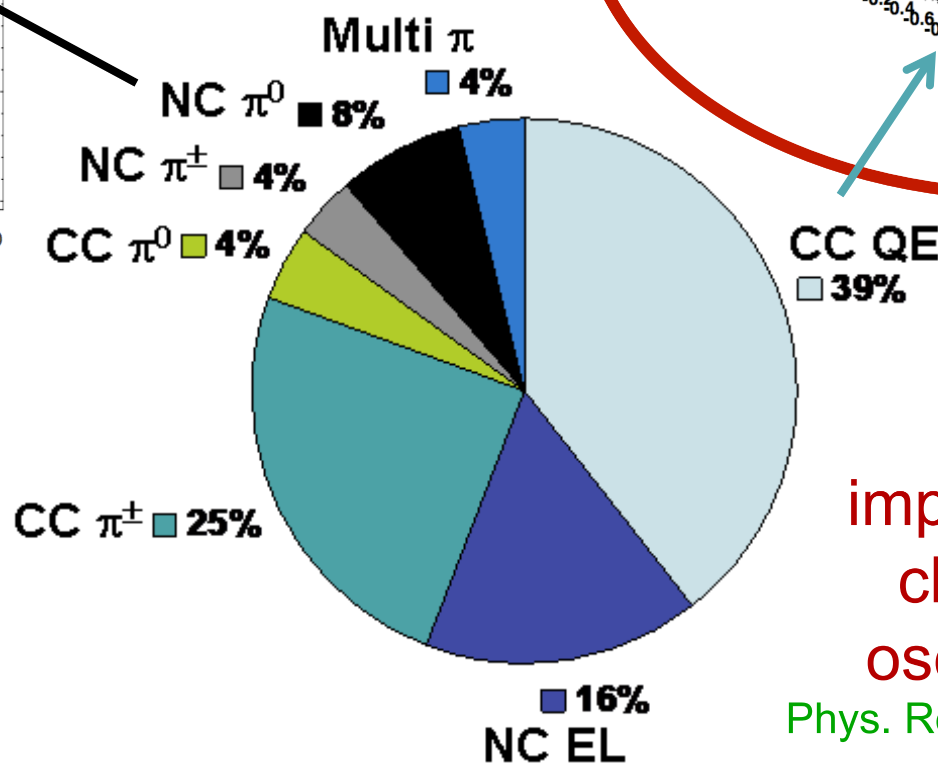
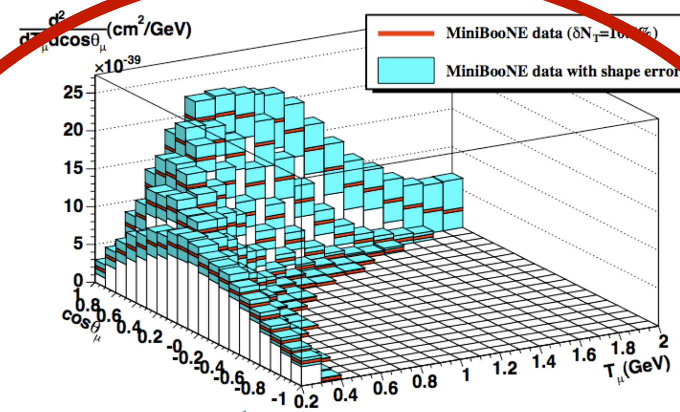


$\nu_\mu\ N \rightarrow \nu_\mu\ N\ \pi^0$





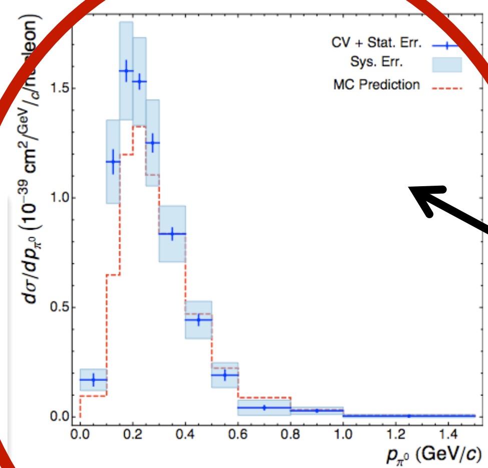
$\nu_\mu\ n \rightarrow \mu^-\ p$

important **signal** channel for ν oscillation exps

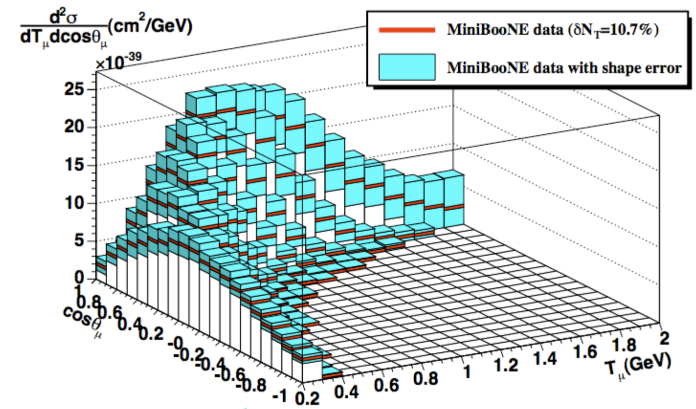
Phys. Rev. D81, 092005 (2010)

Neutrinos in Oil

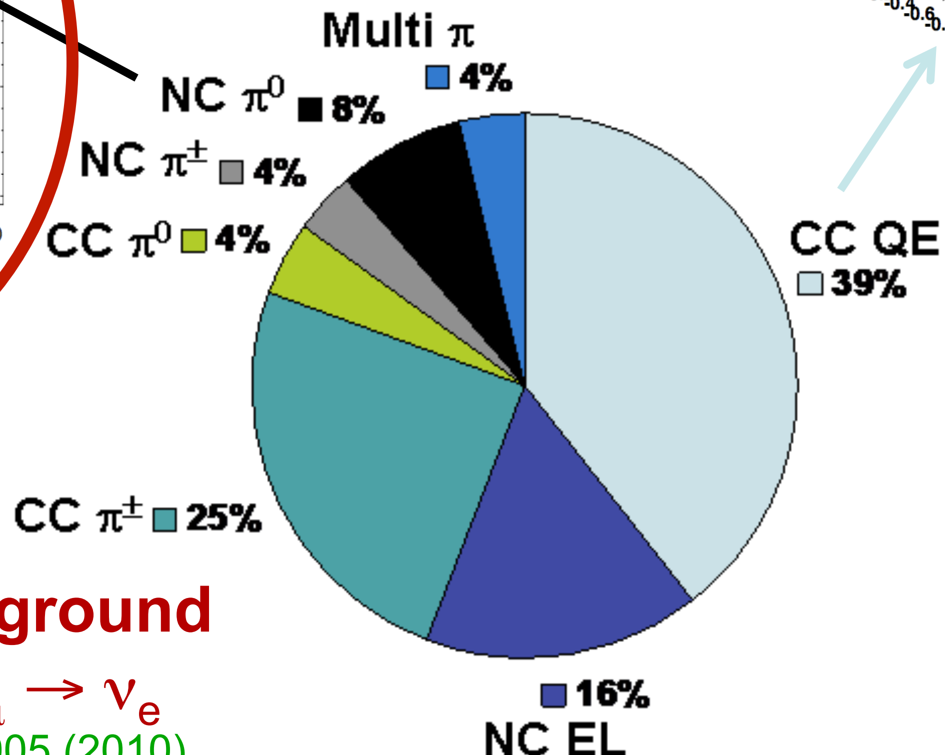
- ν's can do many things in mineral oil



$\nu_\mu\ N \rightarrow \nu_\mu\ N\ \pi^0$



$\nu_\mu\ n \rightarrow \mu^-\ p$



important **background** channel for $\nu_\mu \rightarrow \nu_e$

Phys. Rev. D81, 013005 (2010)

Detecting ν Oscillations

- if neutrinos have mass, then …

a neutrino that is produced as a ν_μ

might some time later be observed as a ν_e

ν source

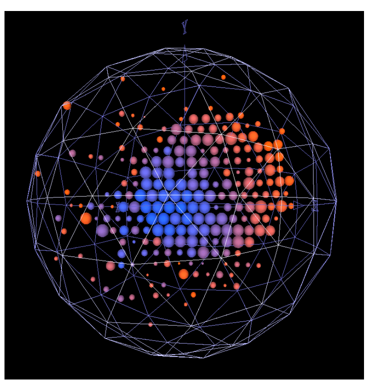
ν detector

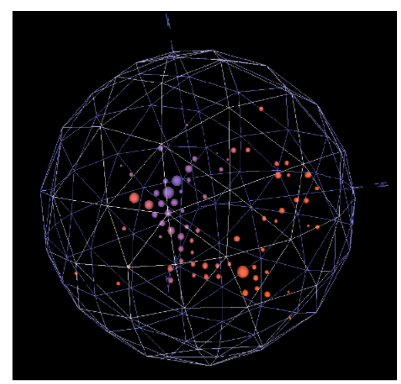
Detecting ν Oscillations

- if neutrinos have mass, then …

a neutrino that is produced as a ν_μ

might some time later be observed as a ν_e





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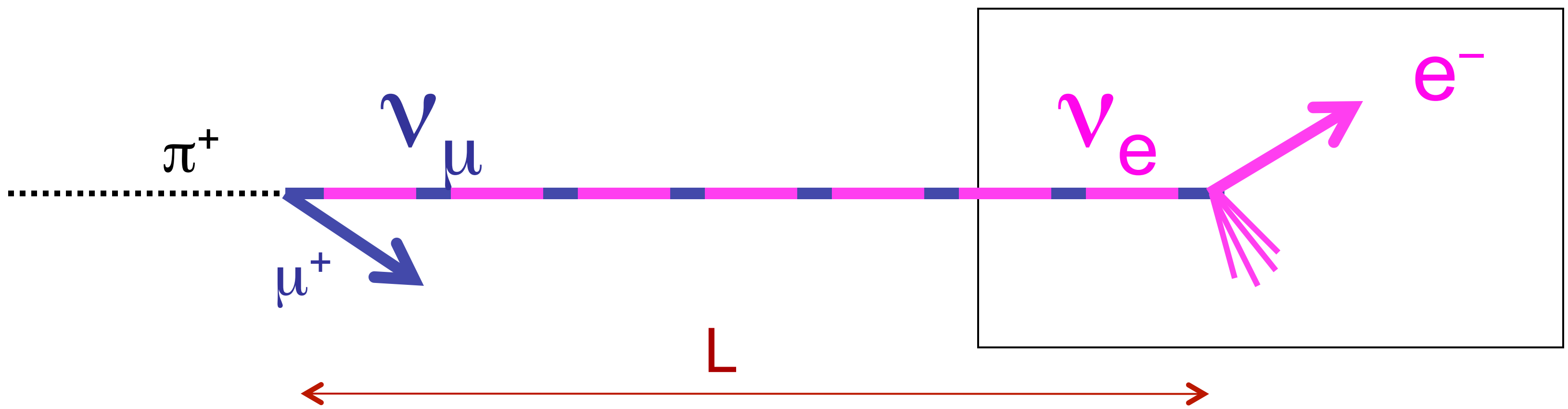


- operate a fixed distance (L), so look as a fcn of E

- start with $\nu_\mu \to \nu_e$, can also check $\overline{\nu}_\mu \to \overline{\nu}_e$ (LSND signature)

MiniBooNE $\nu_\mu \rightarrow \nu_e$ Search

<u>spent many years:</u>

- understanding ν flux
- modeling and calibrating detector
- measuring ν ints, including each and every possible background process
- developing PID
- etc.

"blind analysis"

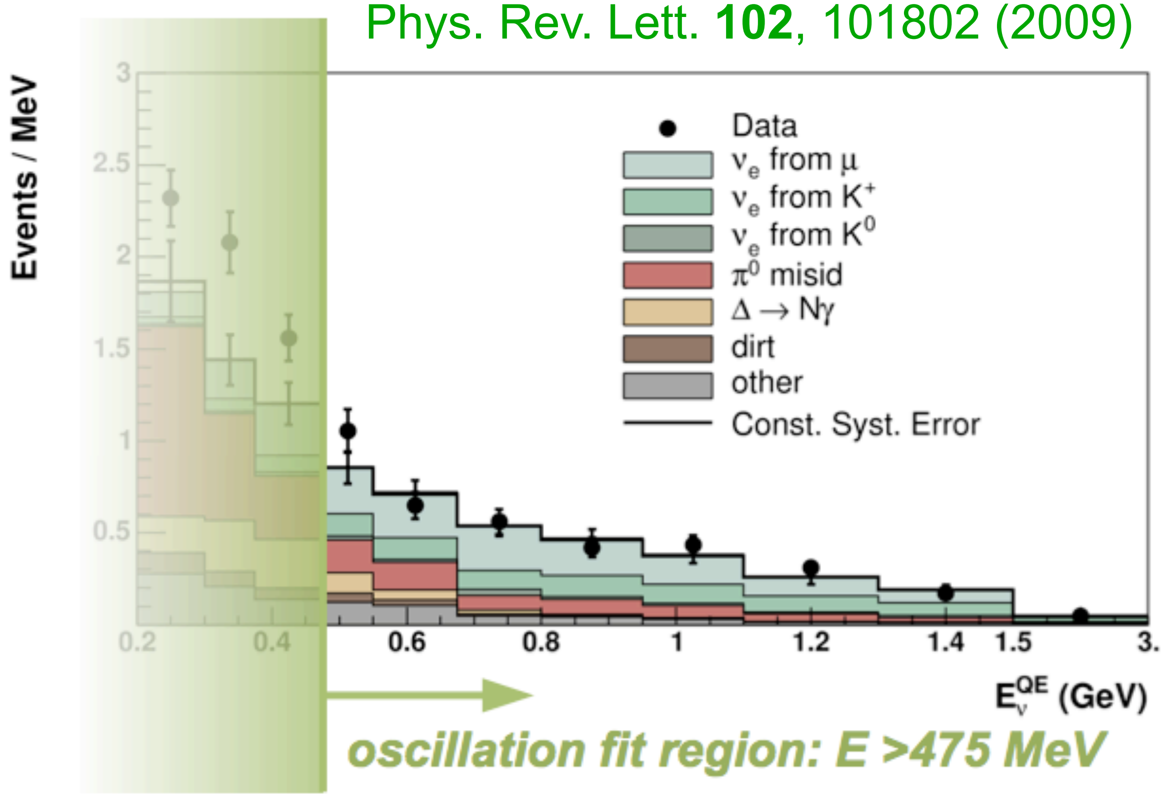
5 years later …

First Results!

Fermilab, April 11, 2007

MiniBooNE $\nu_\mu \rightarrow \nu_e$ Search

Phys. Rev. Lett. **102**, 101802 (2009)

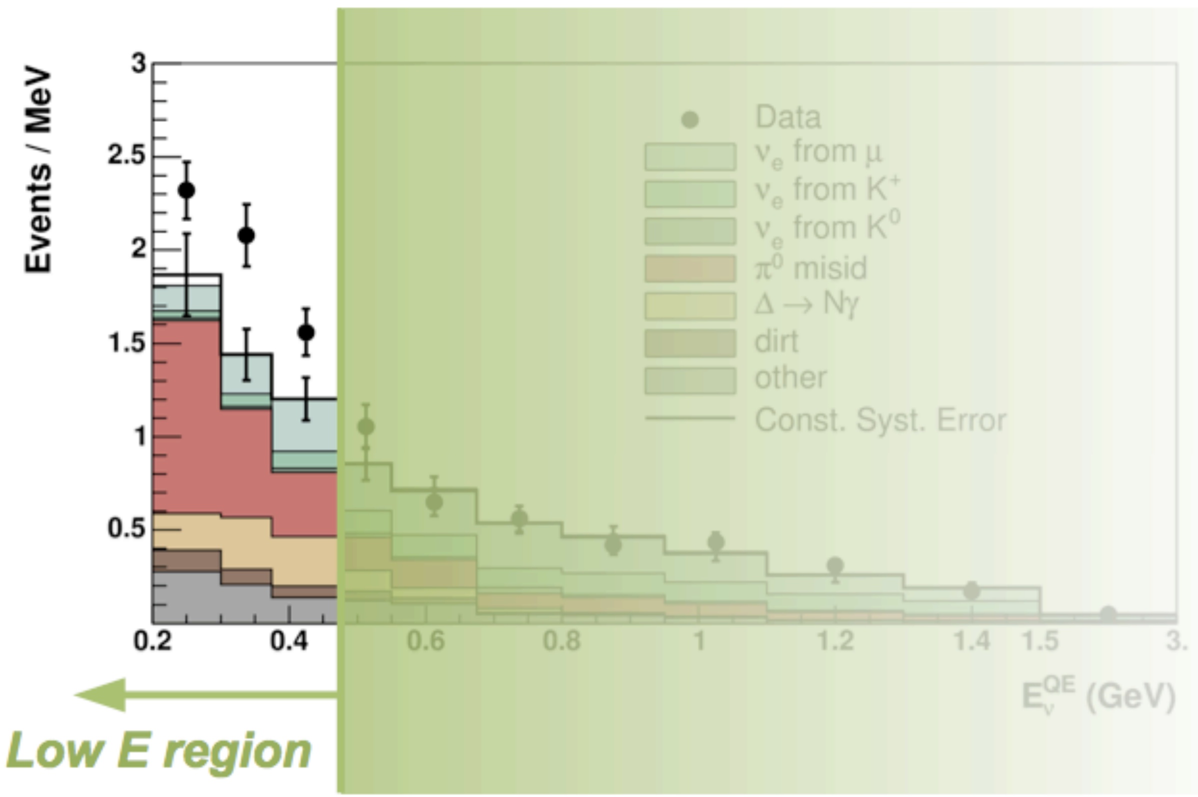


E_ν > 475 MeV
(region where expect to see LSND effects)

no evidence for LSND-like oscillations (2ν)

MiniBooNE $\nu_\mu \rightarrow \nu_e$ Search

Phys. Rev. Lett. **102**, 101802 (2009)

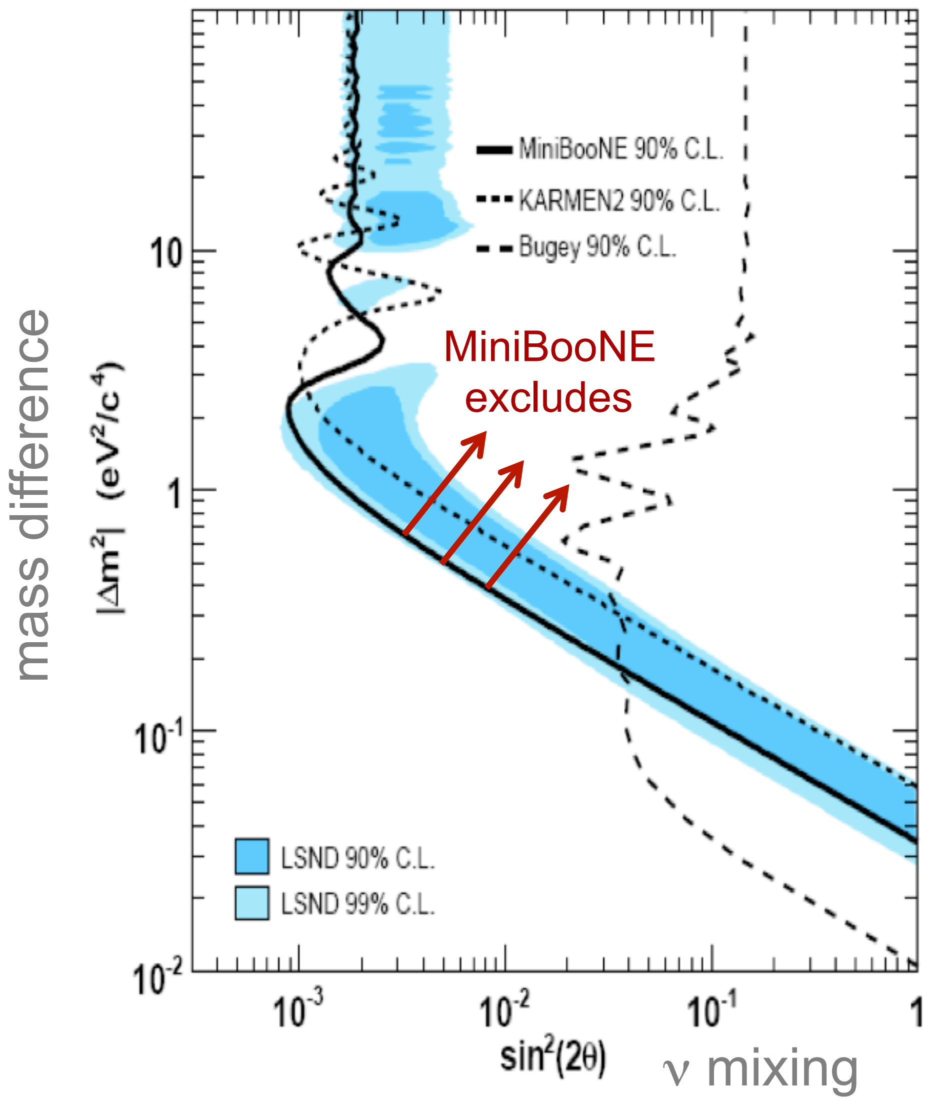


however, observe an **excess** of events at **low energy** whose source is currently unknown

shape is inconsistent with 2ν oscillations

future experiments will test this

MiniBooNE $\nu_\mu \rightarrow \nu_e$ Exclusion Limits



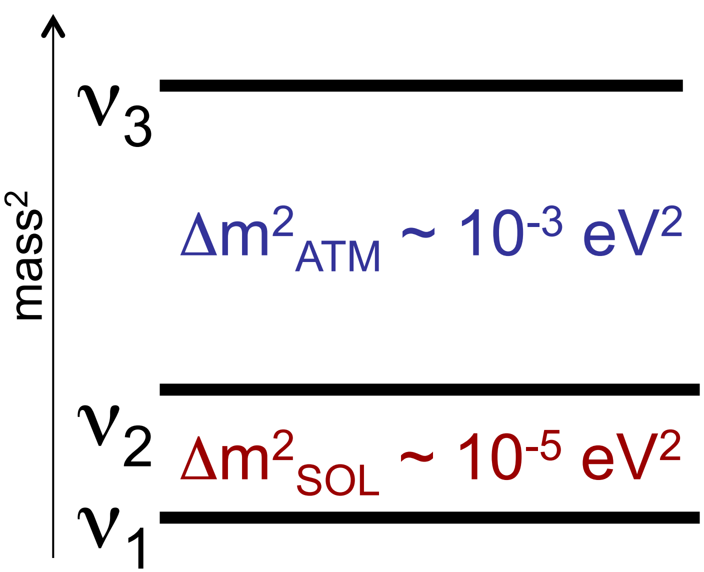
high statistics,
powerful test
of simplest
interpretation
of LSND

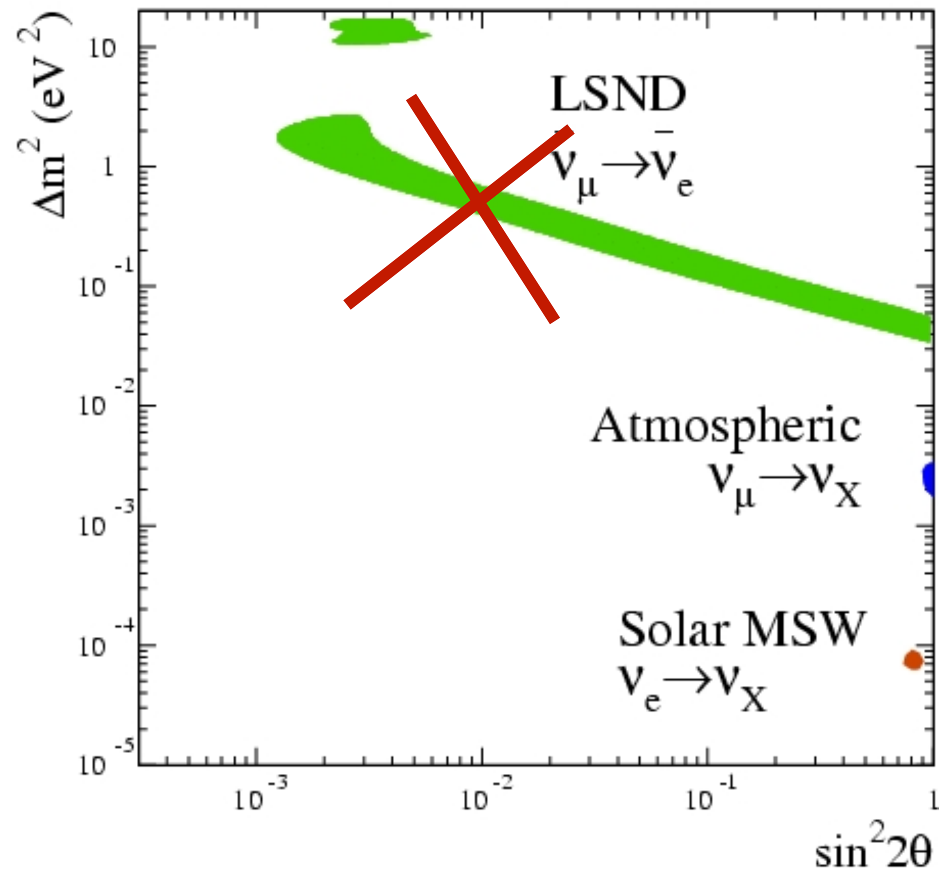
Current Landscape

- remember our picture from before …

- too many Δm^2 regions!

  3 ν's implies 2 indep mass scales:
  $(10^{-3} + 10^{-5} \neq 1)$





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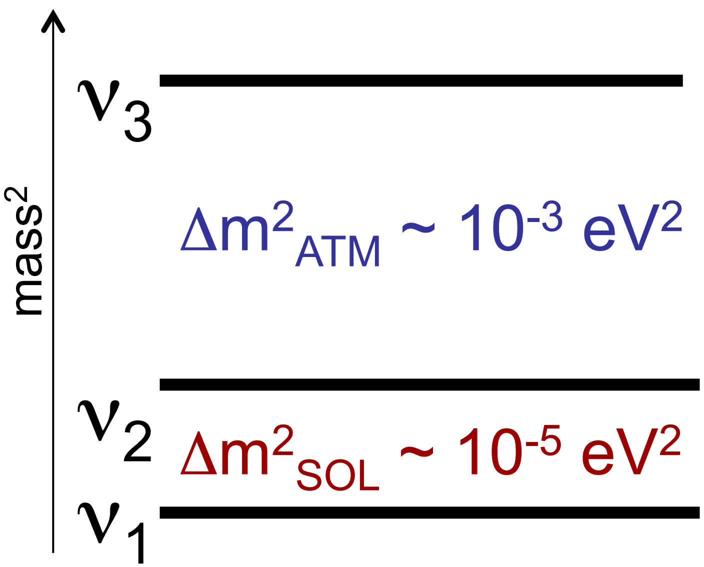
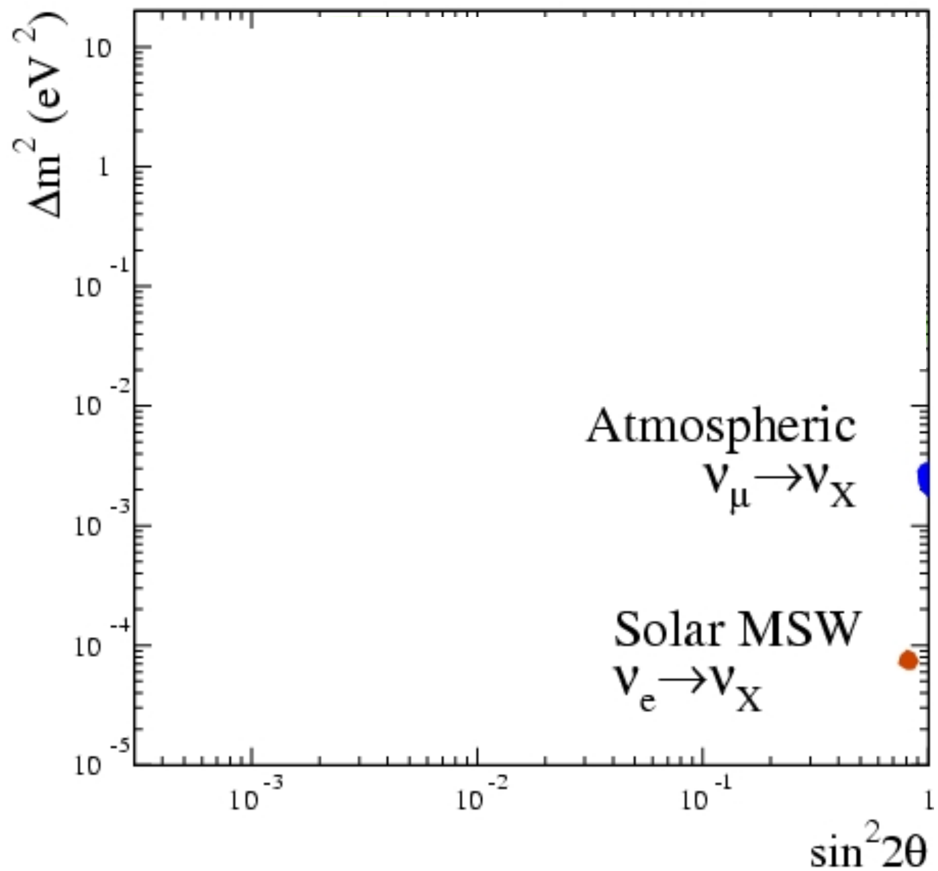
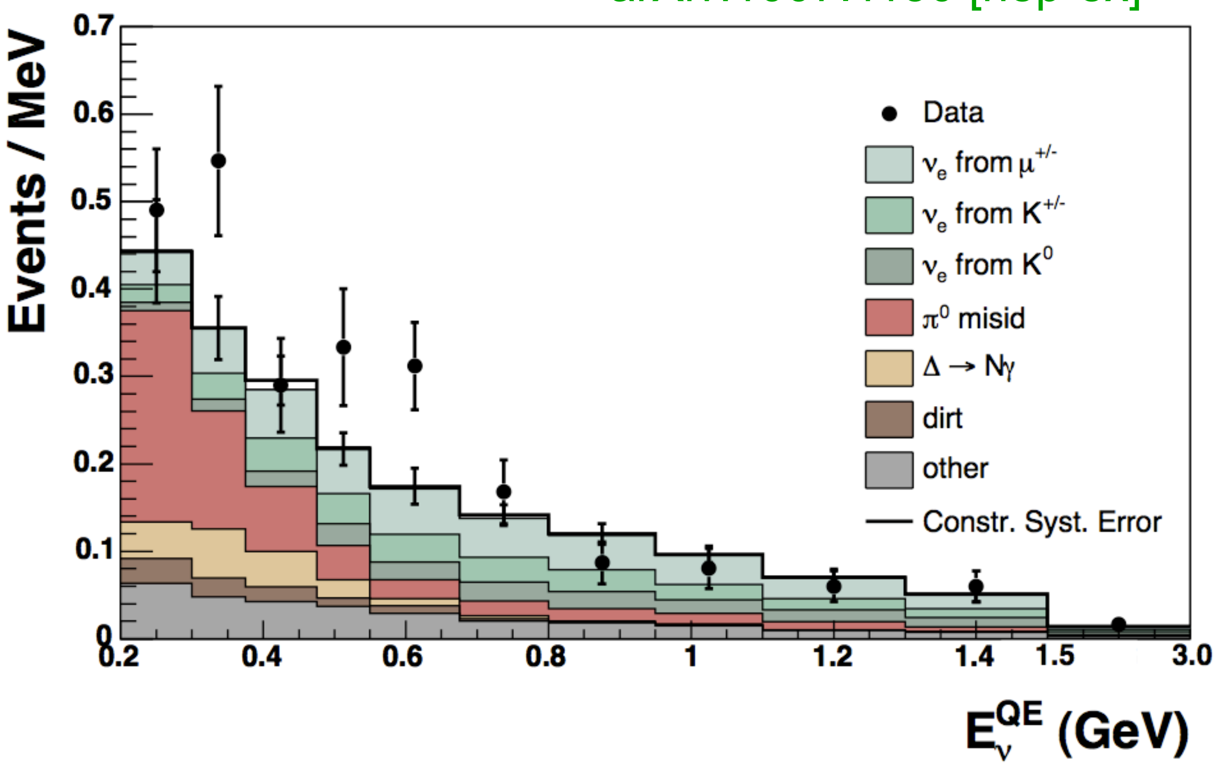




MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Search

• what about antineutrinos? remember oscillations in LSND were originally observed with antineutrinos …

arXiv:1007.1150 [hep-ex]

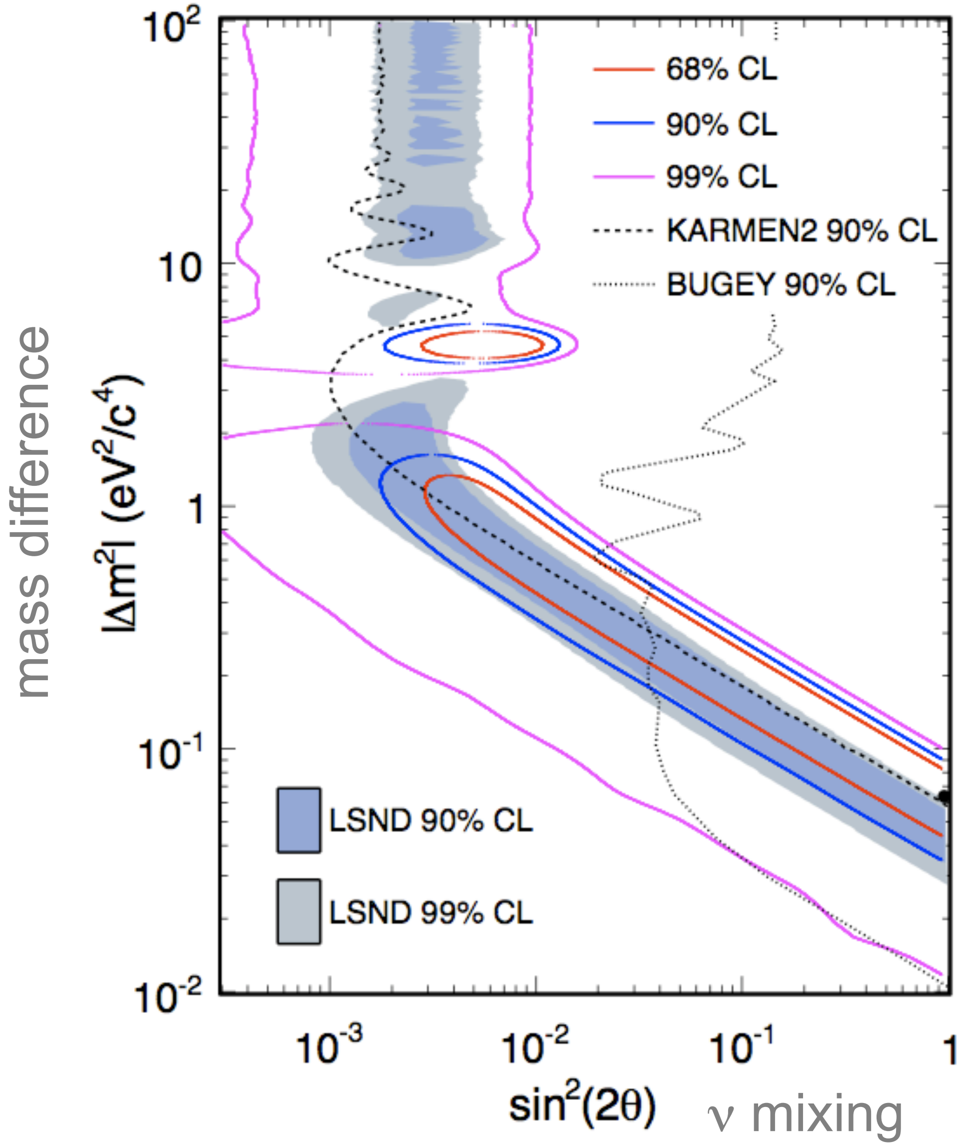


Surprise!

new!
June 14, 2010

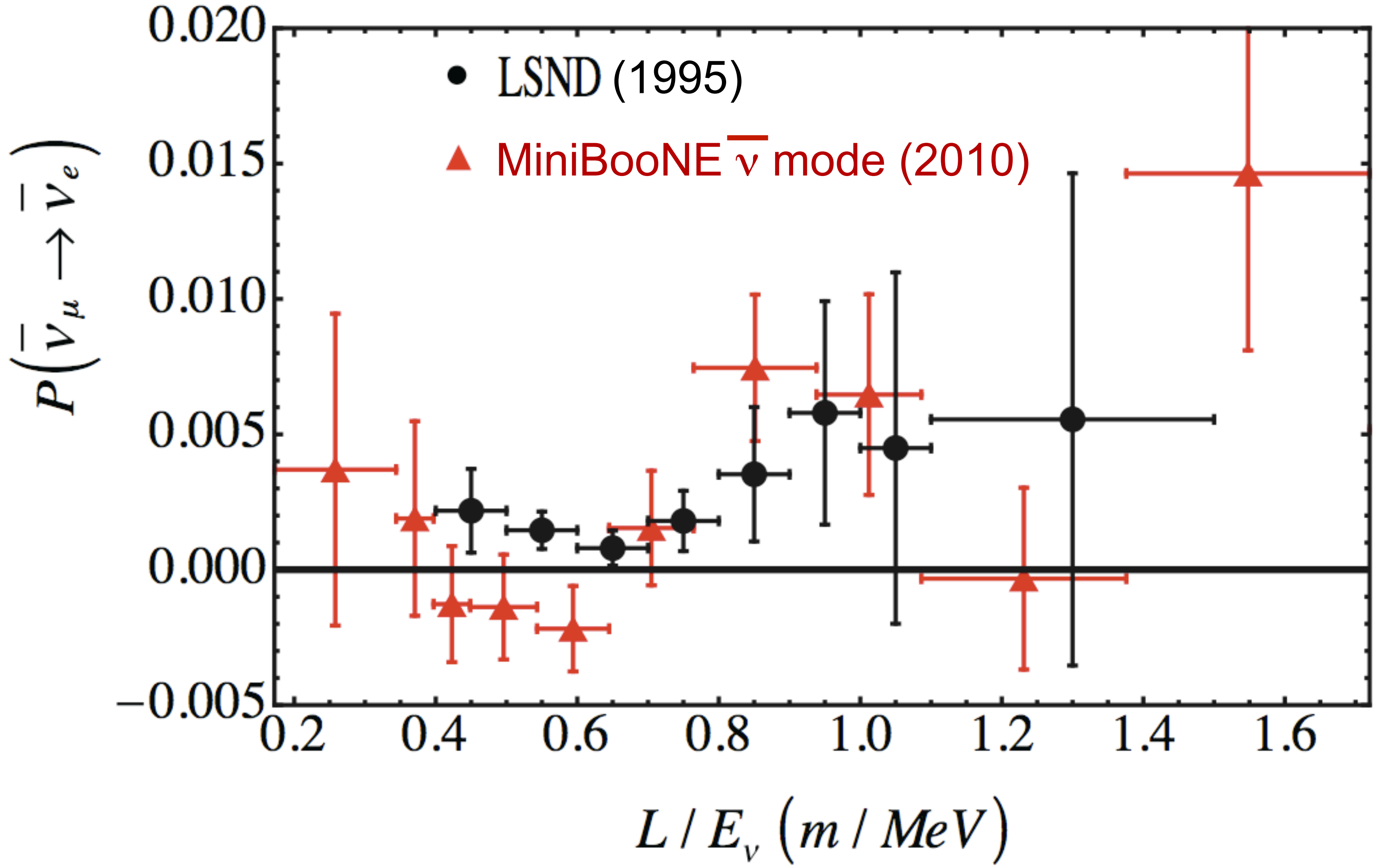
?!

MiniBooNE $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Allowed Region



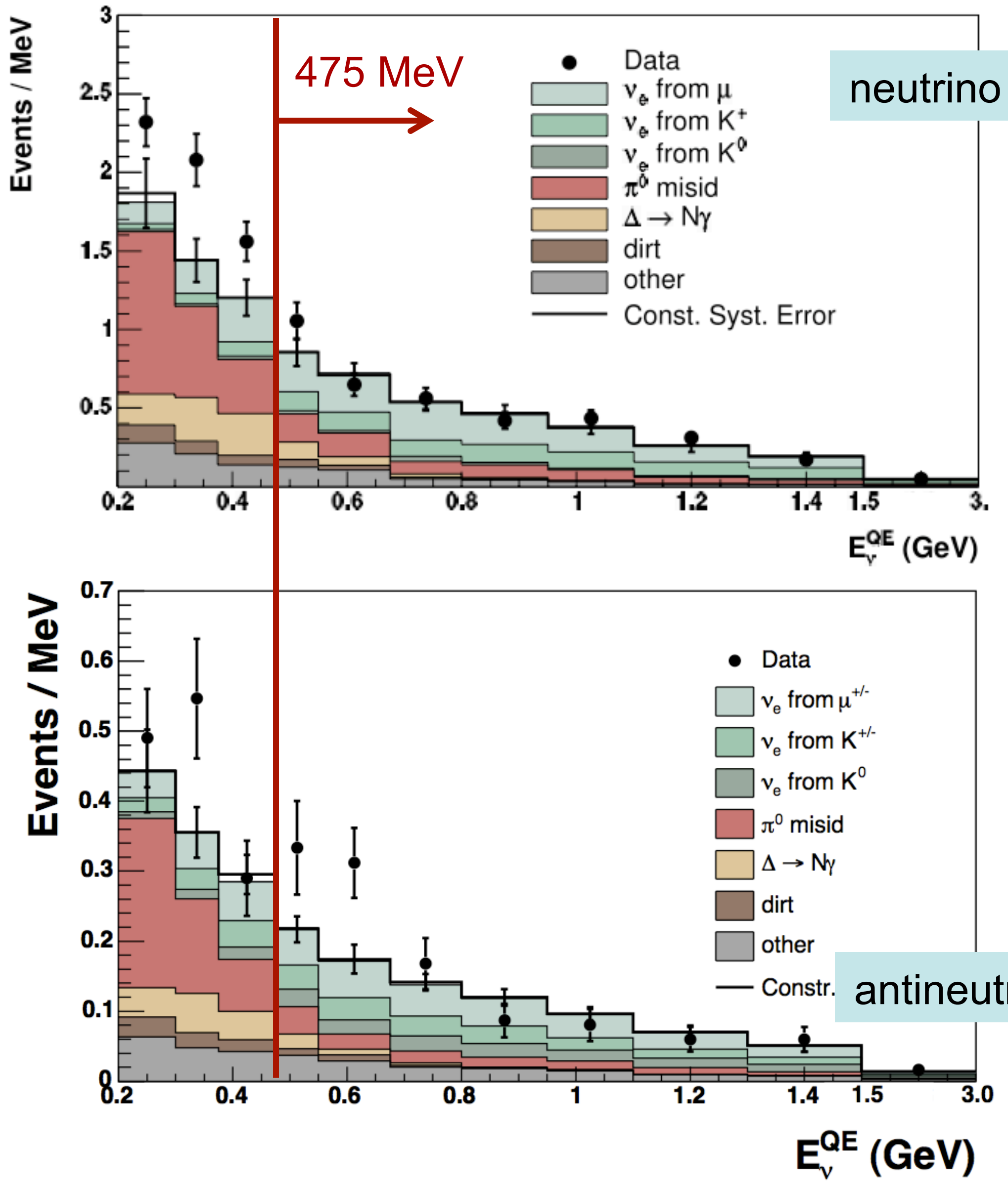
Sam Zeller, Sambamurti lecture, 07/20/10

Comparison to LSND



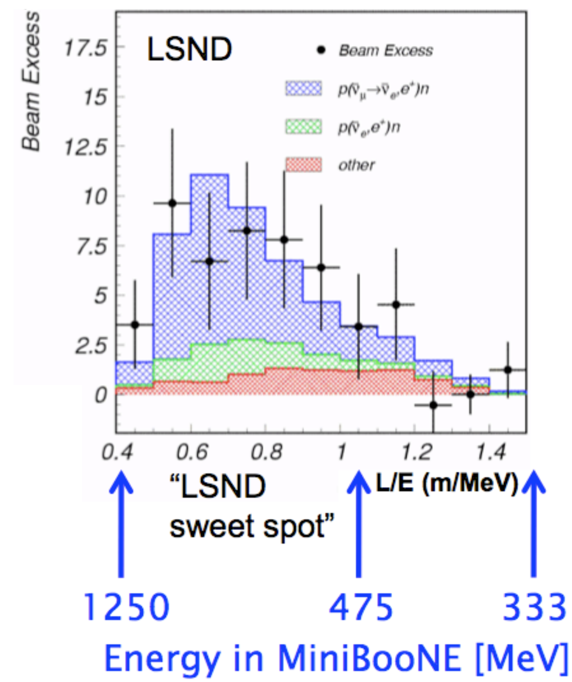
Ahhhhhhhhhh!!!!!

Comparison of MB ν and $\overline{\nu}$



neutrino ν_e appearance (6.5×10^{20} POT)

antineutrino $\overline{\nu}_e$ appearance (5.7×10^{20} POT)



MiniBooNE Scorecard

☑ **ν interaction measurements**

- Phys. Rev. Lett. **100**, 032301 (2008)
- Phys. Lett. **B664**, 41 (2008)
- Phys. Rev. Lett. **103**, 081801 (2009)
- Phys. Rev. **D81**, 013005 (2010)
- Phys Rev. **D81**, 092005 (2010)

1st time have revisited this type of physics in decades

☑ **ν_μ to ν_e oscillations**

- Phys. Rev. Lett. **98,** 231801 (2007)
- Phys. Rev. Lett. **102,** 101802 (2009)

no evidence for LSND-like oscillations (2ν) (low E?)

☑ **$\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillations**

- Phys. Rev. Lett. **103,** 111801 (2009)
- arXiv:1007.1150 [hep-ex] (2010)

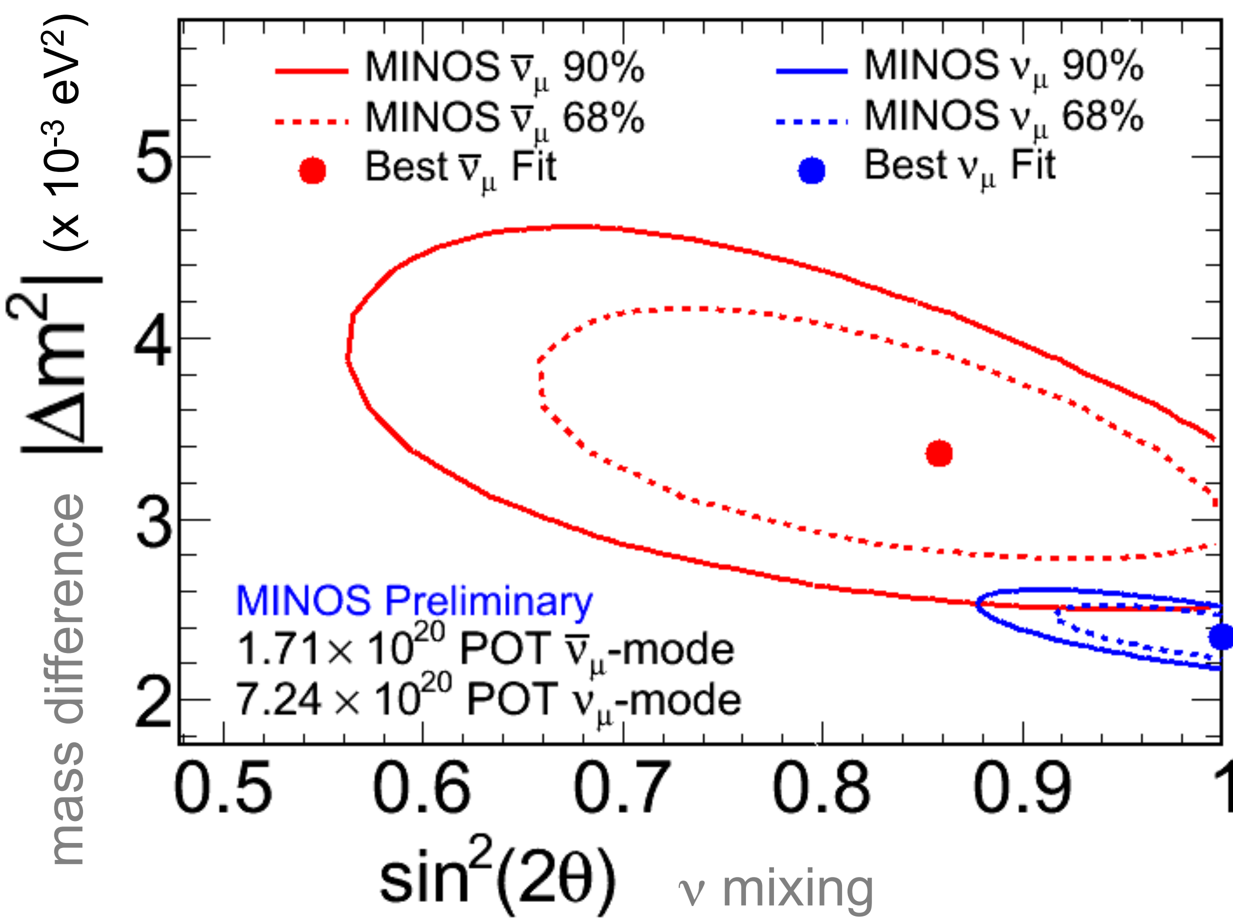
new! results **consistent** with LSND-like oscillations (but need more data)

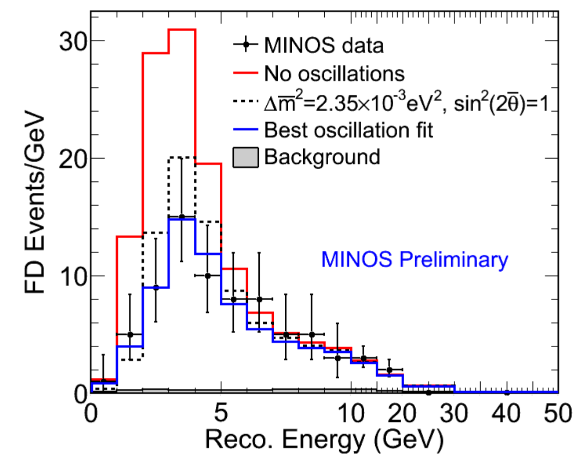
$$\nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e \quad ?$$

MINOS

- other suggestions that ν and $\bar{\nu}$ may be behaving differently?

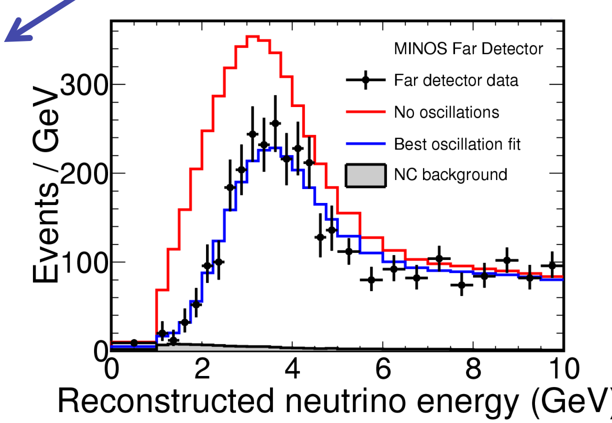
Neutrino 2010: June 14, 2010





antineutrinos

neutrinos



What Next?

- what are the **masses** of the ν's?

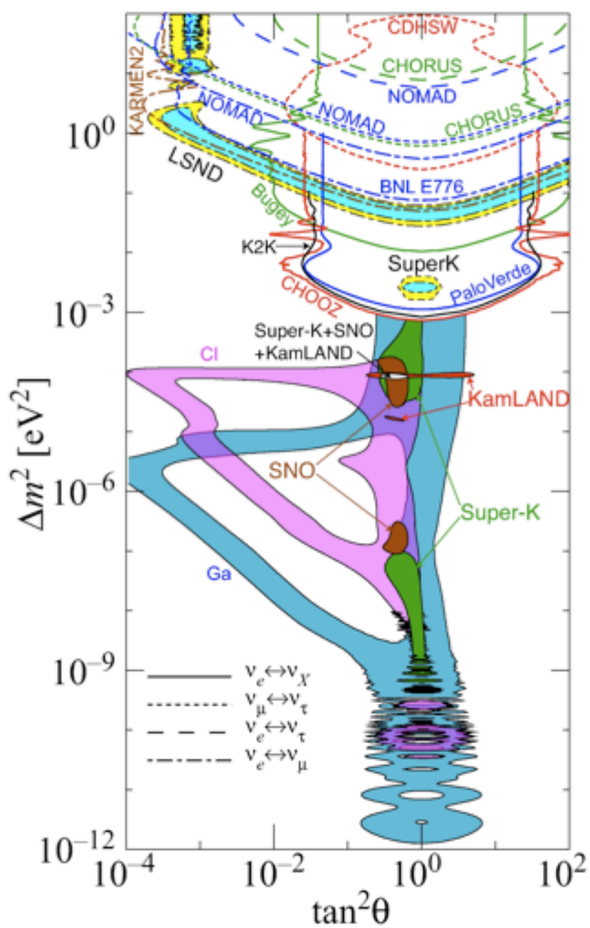
- which are the **heaviest** and which are the lightest?

- what is the exact **pattern of mixing** between ν's?

- do ν's **behave differently** than $\bar{\nu}$'s?

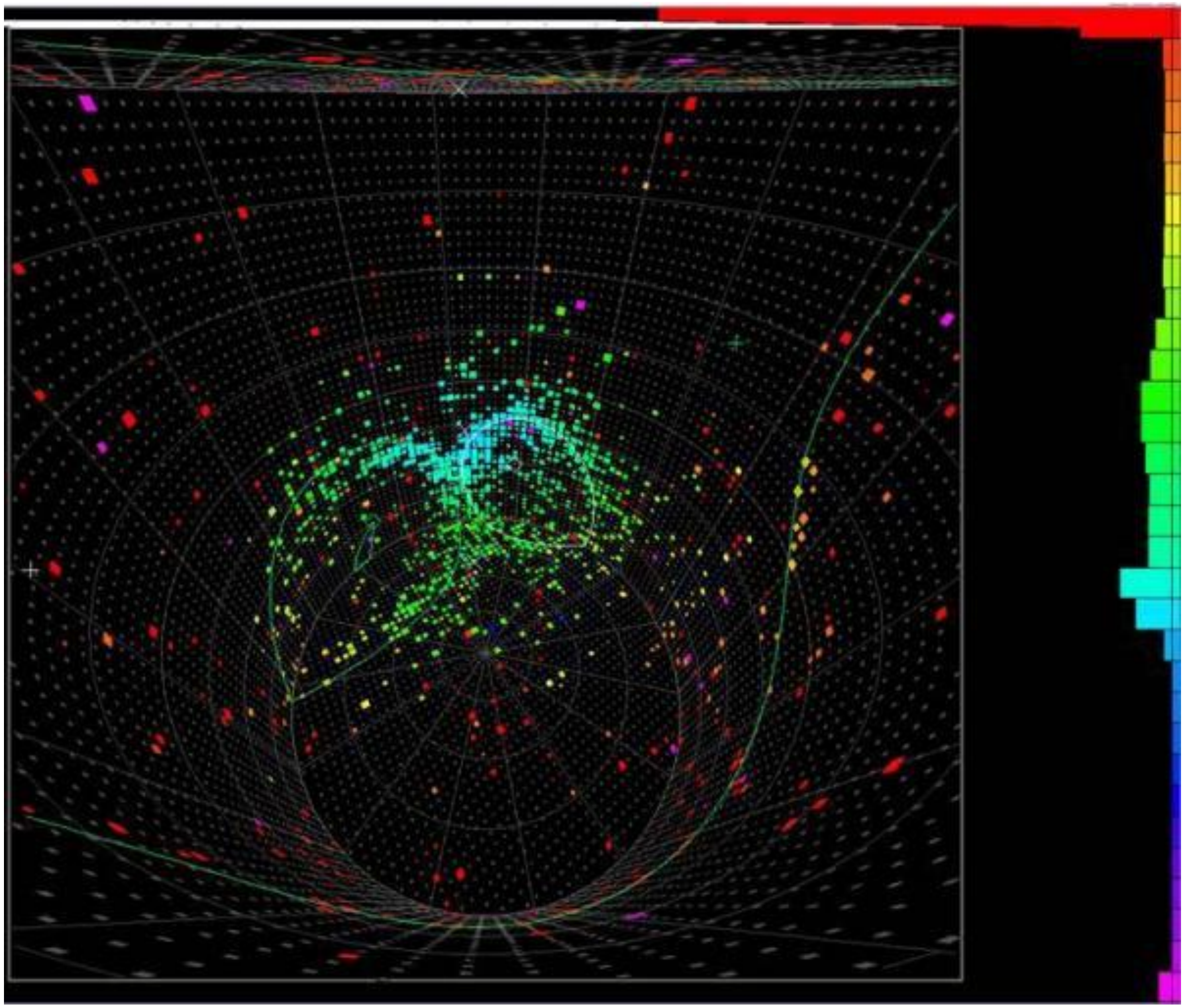
- will we encounter the **unexpected**?

  - neutrinos have been full of surprises, so we should probably expect more!



race is on to study in more depth

It's Been an Exciting Year Already!



$\pi^0 \rightarrow \gamma\gamma$ candidate event

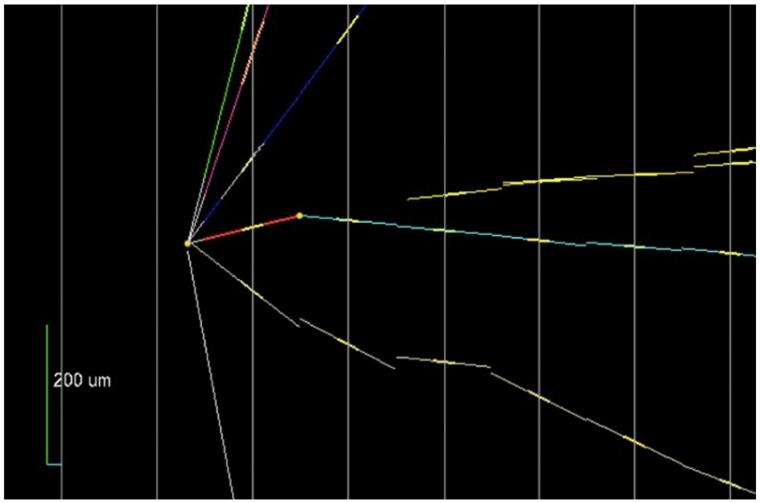
- **T2K**
  Kamioka, Japan

detected their
first neutrinos
(across an 185 mile distance)

Feb 25, 2010

Europe

$\nu \rightarrow$



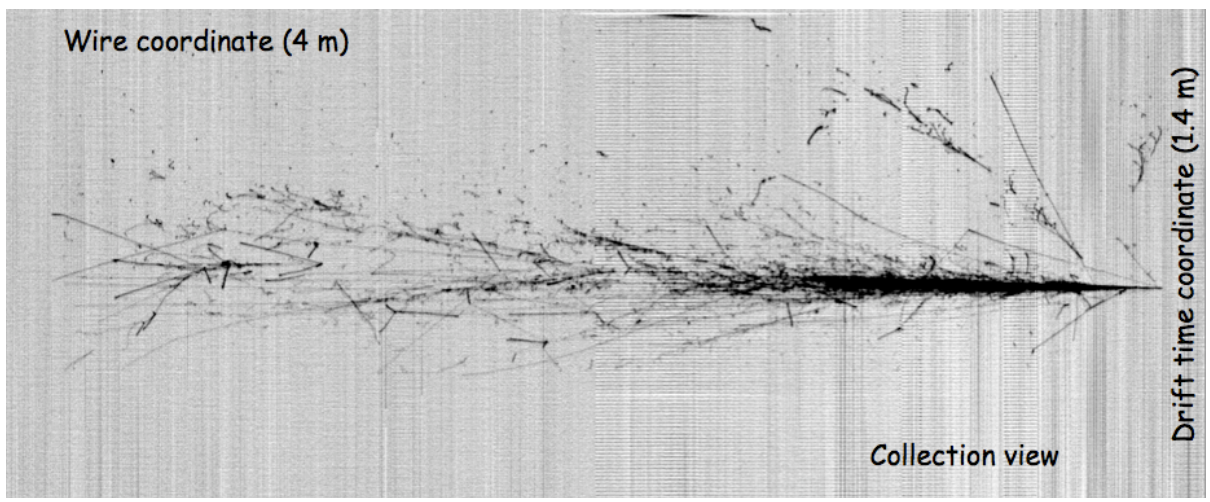
- **OPERA**
  Gran Sasso, Italy

catches 1st evidence $\nu_\mu \rightarrow \nu_\tau$
May 31, 2010

- **ICARUS**
  Italy

1st LBL ν's
in liquid Ar

May 27, 2010



$\leftarrow \nu$

U.S.

- **NOvA**
  Ash River, MN, U.S.

blasting complete
April 18, 2010

U. Minnesota students

U.S.

- **NOvA**
  Ash River, MN, U.S.

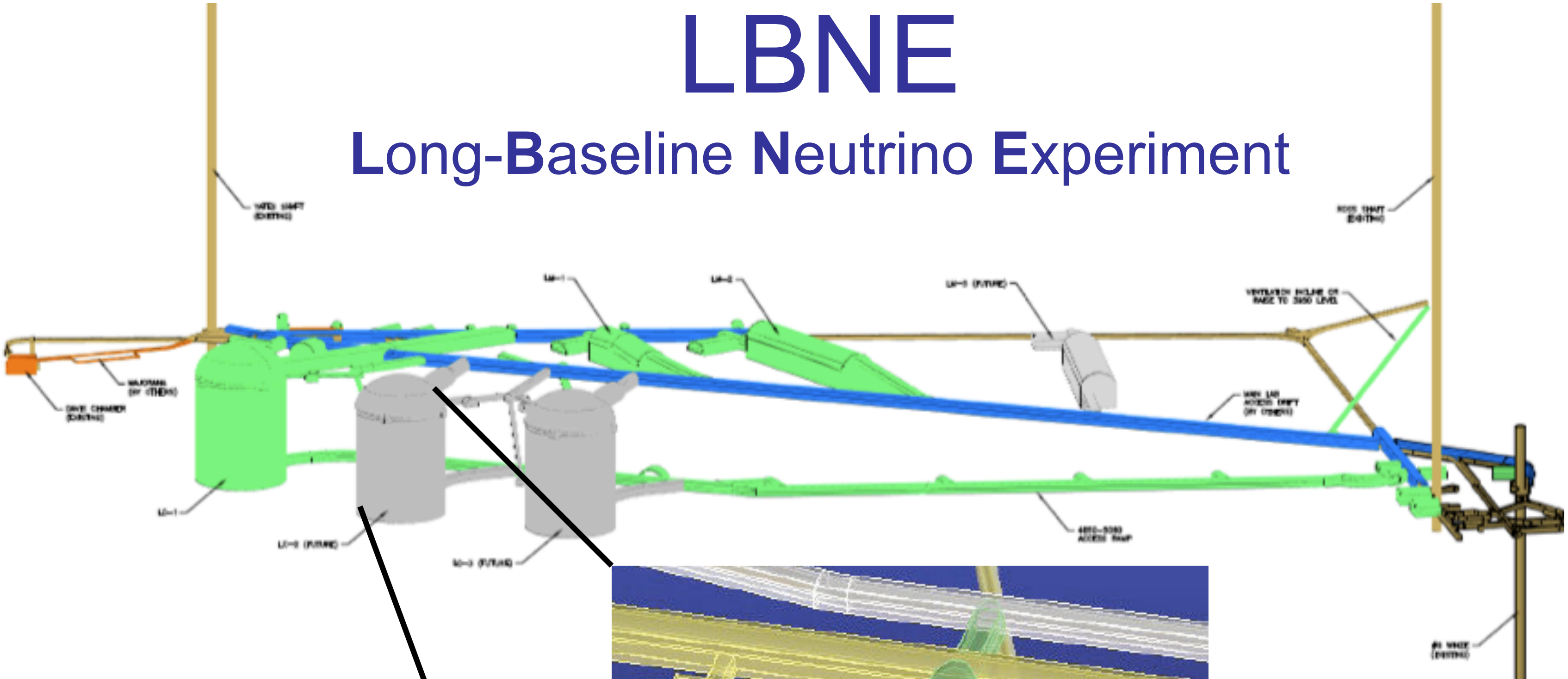
blasting complete
April 18, 2010

- **LBNE**
  Lead, SD, U.S.

DOE CD-0 approval
Jan 8, 2010

LBNE

Long-Baseline Neutrino Experiment



plans to build a
a complex of large
detectors a mile
below the earth's
surface

- 255 scientists
- 54 institutions

Conclusions

- ν's have surprised us with their unexpected behavior for the past ~80 years

  (from Pauli's prediction of the ν to present day observations of ν oscillations)

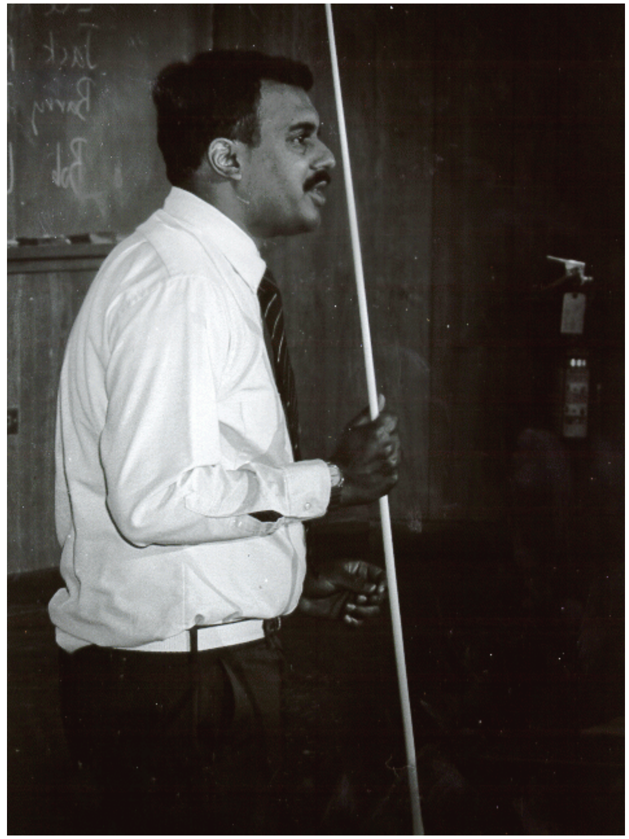
- MiniBooNE has played an important role + with some recent unexpected results

- what will happen in the future is anyone's guess, but it is likely to include more surprises

- this is an incredibly fun time to be a ν physicist ….
  we're in store for an exciting ride!

Come join us!

In Memorium



Aditya Sambamurti
1961-1992